A GOAL-SEEKING APPROACH
TO MODEL THE INJECTION
OF FUTURE VEHICLES INTO
THE U.S. ARMY INVENTORY

THESIS

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THESIS

Presented to the Faculty of the School of Engineering

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Air University

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Master of Science in Operations Research

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Preface

The purpose of this study was to develop a quantitative decision aid to augment the subjective assessment prioritization of future vehicle acquisition. This study was done in support of the TRADOC Program Integration Office for Heavy Force Modernization (TPIO-HFM) at Fort Leavenworth, Kansas.

I would like to thank COL Steve Inman and Mr. Dwain Skelton (TPIO-HFM) for sponsoring this thesis study. I extend my sincerest gratitude and appreciation to the members of my thesis committee, Dr. Yupo Chan and MAJ Michael W. Garrambone, USA. Both gentlemen provided me with superior technical expertise, generous patience and an invaluable learning experience.

Finally, I would like to thank my wife Leighann for her patience and support during this research.

This research is dedicated to the memories of Mr. and Mrs. Walter Hamilton, Mr. and Mrs. Peter DiSalvo, and Mr. and Mrs. Walter Little.

Joseph P. DiSalvo

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Abstract

The purpose of this ~~study~~ Thesis was to develop a quantitative decision aid to augment the subjective assessment prioritization of future vehicle acquisition. The objective of this study was to develop a quantitative methodology that models the acquisition of future vehicles into the U.S. Army inventory.

Instead of establishing inventory levels based on individual vehicle priorities, this study approached establishing inventory levels based on mission priorities. By using a Goal-Seeking Multiparametric Decomposition model, an illustrative example was processed, resulting in specific inventory levels for all vehicles peculiar to an associated mission. Sensitivity was conducted to demonstrate how the inventory levels were effected as the priorities of each mission changed.

This study has shown that a "mission" oriented approach to vehicle acquisition modeling supports the current U.S. Army warfighting doctrine and combined arms operations tactics. This study also found that the "mission" oriented approach fosters a less controversial subjective assessment of future vehicle acquisition into an inventory than the "vehicle prioritization" approach.

CHAPTER 1: BACKGROUND AND RESEARCH PROBLEM

General Background

The U.S. Army is currently executing its Heavy Force Modernization (HFM) program in support of its future warfighting concept. The HFM program considers existing and future armored systems in structuring the future modern armor (heavy) force (28). The U.S. Army's current warfighting concept is called AirLand Battle (ALB). This approved doctrine will evolve to AirLand Battle-Future (ALB-F) (29). The ALB-F "concept" incorporates the present AirLand Battle tenants of agility, initiative, depth, and synchronization (as outlined in FM 100-5: Operations, the Army's primary warfighting concept manual), and recommends augmenting endurance as its newest tenant (14).

The Army's HFM program is focused on injecting into the inventory a family of armored vehicles that will provide the required mobility, survivability, and lethality necessary for successful realization of the ALB-F concept (18). These armored vehicle systems which project the future warfighting capabilities are being concepted to support combat, combat support, and combat service support roles. In the past, the Army has integrated new systems (vehicles) into its inventory on the basis of a single system impact to the inventory acquisition plan (19).

The Army's current objective is to focus on force effectiveness, which means concentrating on the combined impact of all the new systems on the force structure for integration into the inventory (19). This focus on force effectiveness will facilitate the execution of combined arms tactics inherent in the ALB-F concept. Twenty-four HFM systems have been identified, and are categorized as either assault (combat) or assault support (combat support support and combat service support) systems (29). A complete listing fo the twenty-four HFM systems are described in Appendix A. These twenty-four HFM systems will eventually be incorporated into the Army inventory in "packages", where a package represents a grouping of one or more HFM systems.

Presently one HFM package composed of six systems has been identified for funding (19). The methodology used in identifying the components of the first package appears to be based soley on technological availability and the establishment of base chassis' (19). If technical requirements specific to a system were not met within the proposed date of introduction into the inventory, then the "old" methodology simply dropped the system as a component of the package. In an effort to economize on the number of unique repair parts and tools needed, common chassis' have been designed for different systems. Package #1 consisted of common chassis' (providing medium and high

levels of armor protection) of which the heavy chassis and possibly the medium chassis will be retained in the future follow-on HFM systems (11:35). Since no official/ scientific effort has yet been proposed for determining the composition of follow-on packages (19), the Training and Doctrine Command (TRADOC) Program Integration Office for HFM (TPIO-HFM) requires a methodology be developed to prioritize its currently unpackaged HFM systems.

Research Problem

The problem is how best, quantitatively, to construct future HFM packages.

Research Objectives The following list identifies the research objectives of this thesis research:

1. Develop a quantitative methodology that models the acquisition of future vehicles into the U.S. Army inventory.
2. To the largest extent possible, validate the eventual quantitative methodology.

Scope

This thesis research effort is designed to develop a methodology for HFM systems acquisition prioritization, it will not recommend specific figures portraying the actual HFM systems prioritization, except in an illustrative fashion. Current data on eighteen of the twenty-four HFM systems is still being developed as of September 1989. The data will not be available until after the March 1990

time frame (1); therefore, this thesis methodology will process representative data (which will be fully explained in Chapter 3). This thesis research does not address how to develop data pertinent to the essential elements of analysis.

The quantitative methodology will specifically focus on how to prioritize multiple "commodities" (existing and future HFM systems) into a force structure over an extended planning horizon. A force structure is an inventory of systems utilized in the Army. The size of the force structure will be dependent upon many attributes (ie., decision maker's preference, system cost, technological availability, field demand etc.). Attributes can be expressed in constraints (a constraint is a "...temporary fixed requirement which cannot be violated..." (35:225)).

The methodology will be targeted for utilization by an individual who has access to the technical and environmental data (described in chapter 3), and can be processed on a personal computer.

Assumptions

The HFM acquisition process will be assumed to possess linear qualities; therefore, the following assumptions will apply to this thesis research:

1. Proportionality: If a variable (commodity) is doubled, then so are the variable's associated cost and contribution to the constraint (2:3).

2. Additivity: The total cost of all the variables is the sum of the individual variable's cost, and the total contribution to a constraint is the sum of the individual contributions to the constraint (2:4).

It will be assumed the individual using the methodology developed in this thesis research has access to the decision maker's criteria. Thus, valid preferences and goals pertaining to the HFM program can be considered.

Expected Contribution

This quantitative methodology provides a method for optimizing the allocation of scarce resources. In this thesis effort, the acquisition process involves subjecting "commodities" to constraints. As an example, tank acquisition could be limited by cost and force structure requirements (force structure refers to the minimum or maximum quantity of a vehicle necessary for a specific mission's successful execution). In this example, two criteria impact on the resource allocation decision (ie., when and how many tanks should be added to the inventory). Because this research involves more than one vehicle, the quantitative methodology produces discrete decisions from among a finite set of alternatives (24:8). This multicriteria decision making methodology involves examining the feasible solution space delineated by the constraints (2:8). The feasible solution space will be examined from a combinatorial rather than an exhaustive

search approach. Instead of examining every feasible point in the feasible solution space (referred to as total enumeration) a subset of the feasible points will be examined, resulting in shorter solution processing time (24:8). More importantly, the methodology will present decision makers a set of viable alternatives for closer examination, including trade-offs between the multiple objectives. Additionally, the eventual quantitative methodology will possess flexibility so revised constraints and/or specific vehicle(s) emphasis can be processed.

Remark

This thesis research is being sponsored by the United States Army Training and Doctrine Command Program Integration Office for Heavy Force Modernization (TPIO-HFM), Fort Leavenworth, Kansas.

CHAPTER II: LITERATURE REVIEW

Review of U.S. Army Vehicle Acquisition

The applicable literature pertaining to multiple vehicle acquisition modeling in the U. S. Army is limited due to the U.S. Army's recent (1986) revision of its acquisition ideology (13). The current U.S. Army acquisition ideology focuses on developing and implementing a force capable of defeating the threat through the 1990's (13). A modern force composed of many interacting new systems has shifted the acquisition ideology from assessing single system impacts to evaluating the more complex combined systems impacts on future force structure (19).

The AAMTOR Study. The most informative and most current literature on U.S. Army vehicle acquisition modeling is contained in the Army Aviation Modernization Trade-Off Requirements (AAMTOR) study, conducted by the U.S. Army Concepts Analysis Agency (CAA) in 1988. The purpose of the AAMTOR study was to develop a decision aid for force structure planners that could assist in evaluating the effectiveness of the aviation modernization program (33:1-1). The aviation modernization program consisted of replacing the current fleet of helicopters with future models over a twenty-five year planning horizon. The AAMTOR study's relevance to the HFM program is centered on the similarity

of both programs' concern for injecting multiple systems in the inventory with combined impacts on force structure (ie., both programs follow the same acquisition ideology) (28). In the AAMTOR study, CAA defined the following essential elements of analysis (essential elements of analysis are basically measures of effectiveness) (33:1-3):

1) Procurement/retirement schedule: Procurement refers to how many new systems should be acquired over a specified amount of time. Retirement refers to the rate at which old vehicles are deleted from the inventory.

2) Annual force composition: Refers to how many of each system is necessary for specific mission(s) accomplishment.

3) Annual expenditures: Costs ranging from fixed costs (production facility operations expenses) to operations and maneuver costs (training expenses). Figure 1 illustrates some of the data that was processed by the AAMTOR study's model resulting in specific values for the essential elements of analysis.

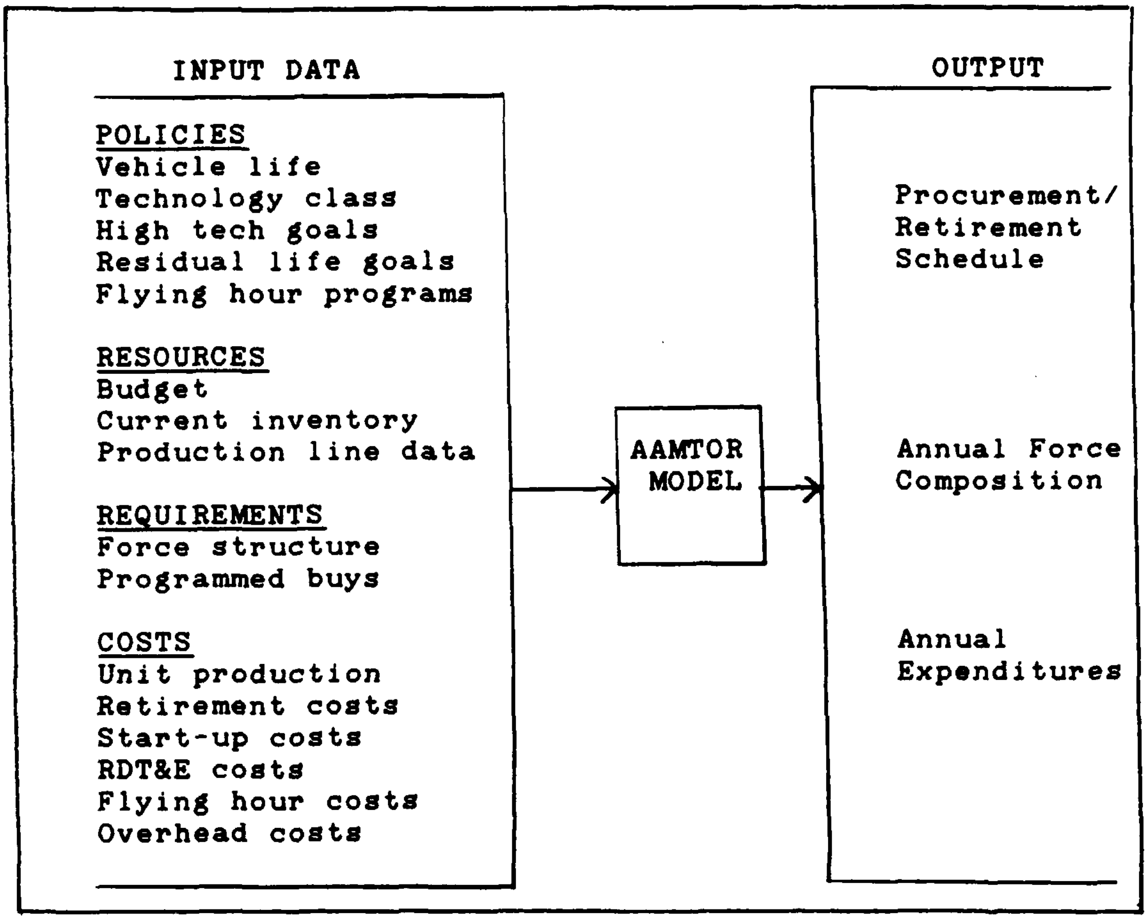


Figure 1. AAMTOR Data Flow

This Army Aviation decision aid (developed by the AAMTOR study) was designed for force planners at the Office of the Deputy Chief of Staff for Operations and Plans (ODCSOPS) level. Specifically, the model developed in the AAMTOR study was a mixed integer linear program containing 288 binary (0,1) decision variables, 9579 continuous decision variables and 3737 constraints (33:3-10). Although the AAMTOR study was conducted by a major subordinate headquarters with an external analytical team resourced far beyond the scope of this thesis research, this study

provides valuable insight with respect to data collection, problem formulation, and essential elements of analysis pertinent to vehicle acquisition.

HFM Data Collection

Obtaining data necessary for modeling the acquisition process is extremely complex. Before data can be defined and collected, highly sensitive issues must often be adjudicated. Replacement vehicle production provides an example of how difficult it is to resolve complicated issues that in-turn directly influence data pertinent to the essential elements of analysis. In production, the Department of Defense must identify which production facilities should manufacture the replacement model, the nature of the facility (government owned contractor operated or contractor owned contractor operated), and what manufacturing equipment should be used (3:9). These production questions lead to a plethora of sensitive issues that range from quality control responsibility to Congressional pressure in support of individual districts (ie., lobbying to keep an existing production facility open or relocating a new production facility). Definition and collection of data cannot begin until these types of issues have been settled. The HFM program's essential elements of analysis have not been completed at this time because several sensitive issues are still pending resolution (22).

Other military related literature reviewed concerning vehicle acquisition were more oriented towards the sustainment that is: 1) vehicle replacement policies (12); 2) stockage levels of repair parts and operational rates (34); and 3) inventory management and life cycle costs (15).

The above topics all necessitated the determination of authorized vehicle quantities so that sustainment analysis could be accomplished. This literature did little to support this thesis research because it addressed only topics which take place after force structure levels have been determined. One document did however mention types of data/information needed for analysis. Among the list of data/information needed was "...priorities of the new assets claimants" (decision makers) (11:1-3). Although there are many decision makers involved in the Army vehicle acquisition process, and if their criterion and priorities are not considered in the acquisition methodology, disparity will surface between what the decision maker(s) desire and what the methodology recommends (13). Recommendations resulting from a HFM vehicle acquisition methodology that ignores the decision makers' priorities will more than likely be dismissed because the methodology failed to include this essential input.

Decision Making Linear Problem Solving Techniques

The basic structure of this thesis research problem consists of optimizing the allocation of scarce resources

to competing activities in a linear domain. It is important to note that linear domain and linear programming are not synonomous. The linear domain (characteristics) invite the use of linear problem solving techniques, such as linear programming (35:215). This portion of the literature review will examine some linear problem solving techniques applicable with this thesis research problem of how best to construct the HFM packages.

One linear problem solving technique is linear programming (LP). Linear programming involves minimizing or maximizing a linear function while accounting for associated linear constraints. The linear constraints can be equality and/or inequality type (2:2). Linear programming problems can be formatted in two ways, either standard form or canonical form. Standard format lists all constraints as equalities and all variables are non-negative. Once a linear problem is put into standard form, the 'simplex' method can be applied to solve the problem (2:5). Canonical form calls for non-negative variables and all constraints being $\geq$ type for a minimization linear programming problem (for a maximization problem, all constraints are $\leq$ type) (2:5). Figure 2 illustrates the Standard and Canonical forms in linear programming formulations (2:6).

	MINIMIZATION	MAXIMIZATION
standard	$\min \sum_{j=1}^{n} C_j X_j$ subject to: $\sum_{j=1}^{n} a_{ij} x_j = b_i$ $x_j \geq 0$ $i = 1, \ldots, m$ $j = 1, \ldots, n$	$\max \sum_{j=1}^{n} C_j X_j$ subject to: $\sum_{j=1}^{n} a_{ij} x_j = b_i$ $x_j \geq 0$ $i = 1, \ldots, m$ $j = 1, \ldots, n$
canonical	$\min \sum_{j=1}^{n} C_j X_j$ subject to $\sum_{j=1}^{n} a_{ij} x_j \geq b_i$ $x_j \geq 0$ $i = 1, \ldots, m$ $j = 1, \ldots, n$	$\max \sum_{j=1}^{n} C_j X_j$ subject to $\sum_{j=1}^{n} a_{ij} x_j \leq b_i$ $x_j \geq 0$ $i = 1, \ldots, m$ $j = 1, \ldots, n$

where: C_j = cost coefficient
X_j = decision variables
a_{ij} = technological coefficients
b_i = min or max requirements to be satisfied
m = total number of constraints
n = number of decision variables

$\min \sum C_j X_j$ is called the objective function

Figure 2. Standard and Canonical Linear Program Formats

The set of decision variables satisfying all the constraints in a linear programming problem constitute the feasible region. Linear programming strives to find all the decision variables located in the feasible region which minimize or maximize the objective function.

If the problem involves more than one objective, linear multiobjective programming can be an applicable technique if the decision maker does not want to choose one objective over the other objective (35:215). On the following page Figure 3 illustrates a linear multiobjective programming format (35:232).

$$\text{min/max: } f_1(x) = c_{11}x_1 + c_{12}x_2 + \ldots + c_{1n}x_n$$

$$\vdots$$

$$f_2(x) = c_{21}x_1 + c_{22}x_2 + \ldots + c_{2n}x_n$$

or

$$\text{min/max } f_i(x) = \sum_{j=1}^{n} C_{ij}X_j \qquad i = 1, \ldots, l$$

$$\text{subject to: } g_1(x) = a_{11}x_1 + \ldots + a_{1n}x_n = b_1$$

$$\vdots$$

$$g_m(x) = a_{m1}x_1 + \ldots + a_{mn}x_n = b_n$$

or

$$g_r(x) = \sum_{j=1}^{n} a_{rj}x_j = b_r \qquad r = 1, \ldots, m$$

$$x_j \geq 0$$

where C_{ij} = gain or loss due to the unit increase in the j^{th} variable with respect to the i^{th} objective

m = number of constraints

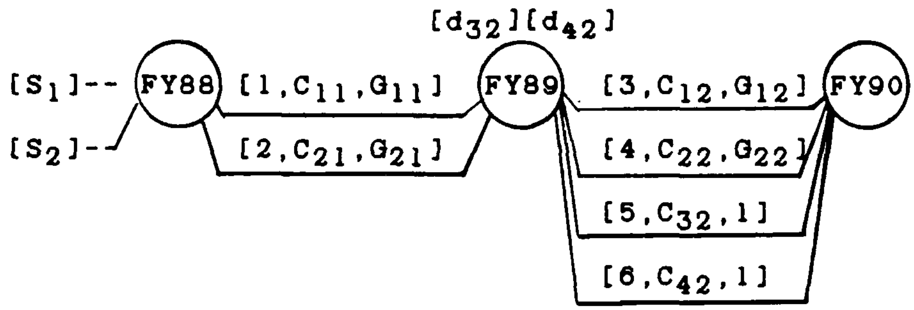
a_{rj} = technological coefficient indicates how much of the r^{th} resource is expended per unit increase in the x_j (j^{th} decision variable).

Figure 3. Linear Multiobjective Programming Format

Linear multiobjective programming (LMP) problems can be processed via multi criteria simplex method (MCS) (35:228). As per Figure 3, inequality constraints can be transformed into equality constraints by applying slack variables when formatting the LMP.

Network analysis is a linear problem solving technique that entails sending some commodity from supply points to demand points. The advantage of using Network analysis instead of the simplex method (hence LP) is that some specialized network flow techniques are more efficient than the simplex method (25:65). Network with side constraints is a specialized network flow technique that can model the vehicle acquisition process. A string of nodes could represent the planning horizon (ie., the fiscal years). Arcs connecting the nodes would specify vehicle unit cost for that fiscal year, and the depletion or conservation of vehicles present that year. Commodities would represent different types of vehicles relevent to the particular inventory. The external demand would represent vehicle supply and demand. Figure 4 illustrates a multicommodity network with side constraints (hence multiattribute) (21:2). In Figure 4, S_i's indicate the number of 'old' vehicle type i's on hand at the beginning of the time horizon. These old vehicles are depleted from the inventory by a factor of G (where G represents a reduction factor that when multiplied by S_i gives the updated number of

vehicle type i remaining in the inventory). The d_{it} vehicles represent new vehicles being injected into the inventory. Notice the d_{it} vehicles have unity gain, therefore their presence is maintained in the inventory (unlike the S_i vehicles, which are being phased out of the inventory). Additionally, the d_{it} vehicles have a limit on how many vehicles of type i can enter the inventory at interval t=2 (as indicated in side constraint (b)). It should be noted that preferences can be depicted in network formulation by specialized constraint formulations (26:33).



where S_i = supply of old vehicle i

d_{it} = demand of new vehicle i at time t

$[j,C_{it},G_{it}]$: j = arc #
C = unit cost
G = unit gain

<u>Side Constraints</u>: $S_{11} + S_{12} \leq b_1$ (a)

$S_{32} + S_{42} \leq b_2$ (b)

Figure 4. Network with Side Constraints

So far, three linear problem solving techniques have been explained, LP and LMP and Networking. Before continuing with other linear problem solving techniques, it is important to formally define a few terms in order to facilitate the understanding of forthcoming techniques. An objective is an unlimited maximization or minimization necessity which must be fulfilled to the greatest extent possible (35:226). There is no reference value associated with an objective. Constraints place limits on the possible values for an objective. Constraints "...divide all possible solutions into two groups: feasible and infeasible" (35:225). Where as objectives are optimized, constraints must be satisfied in terms of their "predetermined values" (35:226). Goals are constraints which must be satisfied in the best way. Constraints can either be satisfied or not satisfied; whereas goals "...allow for fine tuning through their control over the degree of satisfaction" (35:227).

Goal programming (GP) is a linear problem solving technique that focuses on satisfying many objectives as opposed to optimizing a single objective (17:6). GP examines conditions for obtaining predetermined goals (35:248). Predetermination of goals involve assigning priorities to constraints that are being satisfied. The main difficulty in using GP is establishing priority levels for satisfying constraints in the best way possible (17:182). The decision maker must be available to

define the priorities if GP is to incorporate credible prioritizations. Figure 5 illustrates a generic GP formulation (35:223).

$$\min P_1 d_1^- + P_2 d_3^+$$

$$\text{subject to: } a_{11}x_1 + a_{12}x_2 + d_1^- = b_1$$

$$a_{21} + a_{22}x_2 \leq b_2$$

$$a_{31}x_1 + a_{32}x_2 - d_3^+ = b_3$$

$$x_j \geq 0 \qquad (j=1,2)$$

where P_1 is first priority, P_2 is second priority

d_1^- is underachievement 'deviational' variable

d_3^+ is overachievement 'deviational' variable

* note: the first equation is called the 'achievement' function

Figure 5. Generic GP Formulation

In Figure 5, the highest priority is to maximize the utilization of the decision variables (x_1 and x_2) in the first constraint; if this goal is met, then minimize the overutilization of the decision variables in the third constraint. Using GP characteristics illustrated in Figure 5, the following statements can be made that distinguish GP from LP and LMP (32:282): 1) objectives are goals; 2) priorities are applied to the accomplishment of goals; 3) the use of deviational variables d_i^+ and d_i^- are used to quantify overachievement and underachievement from the target levels (b_i) of the goals; and 4) the

minimization of the sums of the deviational variables are used to best satisfy the goals (ie., the achievement function in GP is always minimized).

Although Figure 5 is titled "Generic GP Formulation", the achievement function illustrated actually represents one of two basic GP achievement function formulations. One method is called Pre-emptive (or Lexicographic) GP. In Pre-emptive GP, goals are grouped via priorities. Goals at the highest priority are "infinitely" more important than lower priority goals (32:292). Goals are rank ordered and no other conclusions can be stated (analogous to ordinal scaling) (35:131). The GP formulation in Figure 4 is Pre-emptive. Pre-emptive GP can be solved iteratively using the standard simplex method or solved in one step using lexicographic simplex methodology. One hazard that can surface when using Pre-emptive GP is when a unique solution results prior to a lower priority goal's processing. In this case a lower priority goal will not get the chance to influence the solution (32:294). A major criticism of Pre-emptive GP is its inflexibility because higher priority goals can completely suppress lower priority goal input. One possible remedy is using relaxation quantities in subsequent iterations (32:294).

The second GP approach is called Archimedian GP. In the Archimedian GP achievement function, penalties with different degrees of severity are assigned to the

undesirable deviations from each goal (32:286). Unlike Pre-emptive GP, the entire achievement function is considered simultaneously (35:300). The Archimedian GP strives to limit the total deviational distance from prespecified goals (35:300). The Archimedian GP achievement function for Figure 5 would be as follows:

$$\min\ (w_1 d_1^- + w_3 d_3^+)$$

where w = weight (penalty) assigned to constraint i for deviating per unit d_i from the desired b_i level.

Note that weights w_1 and w_3 are not pre-emptive, they depict the relative contribution of each goal to one another (cardinal relationship).

Both Archimedian and Pre-emptive GP are highly sensitive linear problem solving techniques (32:298). Rotating priorities within a Pre-emptive GP formulation and varying the weights within an Archimedian GP formulation will have a significant impact on the subsequent solutions. Regardless whether one is using Archimedian GP or Pre-emptive GP, establishing ordinal or cardinal relationships can be very difficult, even when the decision maker is available for input. Ordinal scaling techniques such as "psychometric scale" (how one subjectively feels) can be prone to the following errors (9:12): 1) logical errors where "...raters give similar scores on attributes perceived as logically related or similar"; 2) errors of

leniency where every attribute is viewed as important rather than unimportant; and 3) error of central tendency where "... subjects tend to rate items in the direction of the mean " (9:12). The same errors can occur when one utilizes cardinal scaling (ie., analytical hierarchy process) (9:12). The underlining point is a modeler must be aware of possible errors being committed by the decision maker when the decision maker uses ordinal or cardinal scaling in expressing priorities. Additionally, GP is only effective for up to five priorities (if more than five priorities exist the corresponding objectives will have little chance of influencing the solution) (17:182). Correspondingly, if the priorities are to be kept minimal in GP, then so should the number of objectives (17:182).

Multiple Criterion Function GP (MCFGP) is a variation of GP that incorporates Archimedian GP and Pre-emptive GP. The MCFGP process is as follows (32:300). 1) specify goals; 2) form priority levels; 3) assign "within-priority-level" Archimedian weights; and 4) instead of solving the GP lexicographically, solve this GP as a LMP (ie., via MCS).

Summary

The linear problem solving techniques discussed in this chapter can be applicable depending on the environment in which the decision is being made. If the environment is very simplistic (ie., one objective is sought), linear programming can be effective. If the environment is more

complicated (ie., the decision maker is interested in more than one objective), yet "uncontroversial" (all objectives are considered equally important), LMP and Networking could be a reasonable solution approach. If the environment is such that the decision maker is concerned with varied objectives and has a preference among the various objectives, then GP and Networking could be an appropriate technique. Although preferences can be reflected in Networking, GP provides a more convenient method for declaring prefrences. It should be noted that when going from LP to LMP to GP/Networking, the associated environment becomes more complicated and conflicting (hence, real world). GP best reflects the way decision makers actually make decisions in the real world (20:562).

CHAPTER III: METHODOLOGY

General Approach

An appropriate methodology with respect to this research problem of vehicle acquisition must reflect competition among variables for limited resources, consideration of multiple objectives, and decision maker preference. How the decision maker utilizes preferences are contingent upon the environment of the problem. If a known standard exists with respect to the problem environment, then the decision maker can use apriori preferences to facilitate achievement of a solution that is as close as possible to the acceptable standard (35:281). This type of environment (where an acceptable standard exists) is called a goal-setting environment. If known standards do not exist in the problem's environment, then the goals sought are "self suggested" (4). In this case, the decision maker cannot dictate preferences that will affect the solution, instead the decision maker should examine the solutions based on combinations of priorities assigned to the criteria set. A criteria set refers collectively to the attributes, objectives, and goals relative to a specific decision maker in specific situations (5). The decision maker can then select the solution containing the preferred priority

structure. The type of environment where acceptable standards do not exist is called goal-seeking (4).

LP would not prove to be an appropriate solution technique for this thesis because of its inability to process multiple objectives. LMP does offer multiobjective processing capability, but does not consider decision maker preference. Networking can consider apriori preferences (although formulation is difficult), and can process multicommodities and multiattributes (although the more attributes the more complex the formulation becomes). GP may appear to be the most appropriate problem solving technique. Before further comments are made on GP applicability, it is beneficial to discuss the potential solution space.

In the HFM context the decision maker is confronted with examining objectives that include up to 43 primary decision variables (24 HFM vehicles and their associated predecessors). Potentially, a decision maker may have to select a solution from a very large solution space. Refinement of the potential solution space could facilitate the decision maker's selection process. A refined potential solution space contains a set of points which are called nondominant. A nondominant point is part of the feasible set such that "...no other point is feasible at which the same or better performance could be achieved with respect to all criteria, with at least one being strictly better"

(35:68). If a point is not in the nondominant set, it is called a dominant point. Figure 6 illustrates a nondominant set (6). The nondominant (N) set in figure 6 represents the

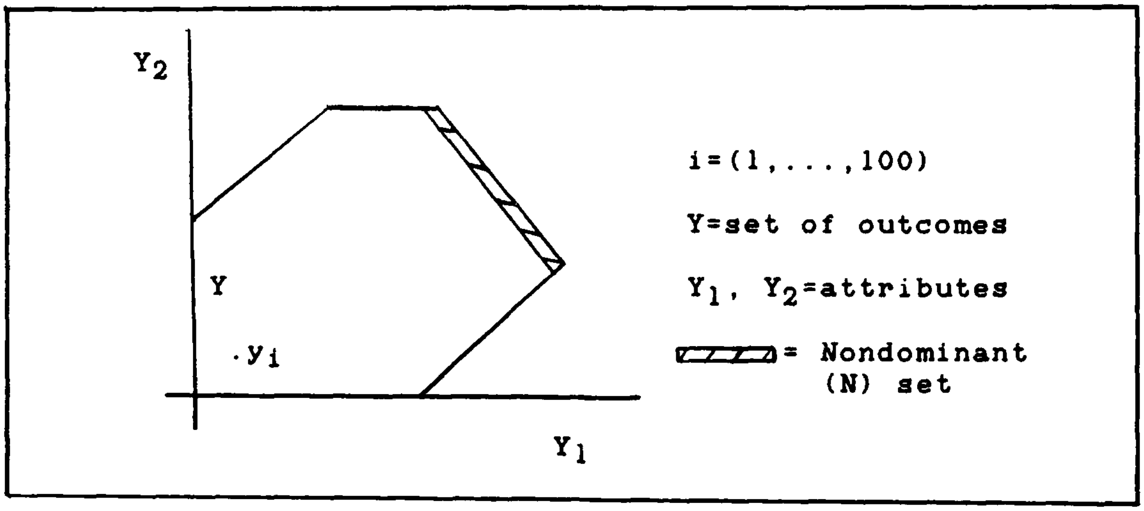


Figure 6. Nondominant Set

"best" set of points a decision maker would need to consider in the decision making process. In Figure 6, rather than examining all 100 points in the outcome space, only the smaller set of nondominant points need to be examined. Isolating the nondominant set allows for a more efficient follow-on examination of potential solutions. Morse offers an excellent definition of a nondominated set:

> When conflicting objectives are simultaneously considered, there is no such thing as an optimal solution. Rather, a preferred class of basic feasible solutions called the nondominant set results" (23:55).

Examination of the N set can be accomplished by a number of techniques, each of which deal differently with the preferences associated with the corresponding criterion composing the N set. If a goal-setting environment exists,

then Pre-emptive or Archimedian GP could be appropriate techniques used to examine the N set for a solution. If a goal-seeking environment exists, then Multiparametric Decomposition (MPD) could be used. MPD is simply an extension of LMP that proceeds to examine preference sensitivity with respect to the multiple objectives.

As previously stated in Chapter I, a major objective in this thesis research is to provide a methodology for prioritizing HFM vehicles for acquisition into the inventory. GP is not an appropriate technique for this thesis problem because apriori preferences are not available to the decision maker (if they were, this study would not be necessary). The HFM vehicle acqusition environment is too new to have acquired acceptable standards; therefore, the decision maker is actually in a goal-seeking environment. Because a goal-seeking environment exists, MPD will be the technique used to prioritize HFM vehicle acquisition.

MPD "alleviates" the problem of assigning apriori priorities to a linear multiobjective problem (35:248). The MPD approach is similar to LMP, except the concerned objectives (criterion set, $f_i(x)$ where $i=(1,\ldots,l)$) are aggregated into one objective function. Additionally, a vector of weights (priorities) represented by λ are appended to the objective function, where $\lambda = (_1, \ldots, _l)$ such that $\lambda_i \geq 0$ and $\lambda_1 + \ldots + \lambda_l = 1$ (35:248). Summarily, this

multiparametric aggregate objective function appears as follows:

$$\max f(\lambda,x) = \max \sum_{i=1}^{l} \lambda_i f_i(x) \qquad i = (1,\ldots,l)$$

The alternative space (referred to as X) is formed by the constraints. These constraints are in the $\leq$ form because the objective function is being maximized. The constraint set would appear as follows:

$$g_r(x) = \sum_{j=1}^{n} a_{rj} x_j \leq b_r \qquad r = (1,\ldots,m)$$

$$x_j \geq 0$$

where r = r th resource
n = # of decision variables
m = # of constraints

j = j th decision variable

Once the aggregated objective function and constraints are formulated, they are put into regular tableau format. Instead of having one "zero row" (as in LP simplex tableau format), in MPD the zero rows are composed of the criteria functions. All but one of the criteria functions are treated like constraints, and the tableau is solved via Multi Criteria Simplex (MCS) procedures. Zeleny presents the MCS process in Chapter 3 and Appendix A of <u>Multi Criteria Decision Making</u> (1982). As each criteria function is optimized, nondominated extreme points of the alternative space X are identified. Additionally, each extreme point of X will correspond to a particular subset of λ, where $f(\lambda,x)$

reaches its maximum value (35:248). By way of MPD, "...the set of all parameters can be decomposed into subsets associated with individual nondominated solutions" (35:248). The major advantages MPD has to offer are as follows (7): 1) MCS can readily identify the N set; and 2) implications of varied weighting assignments can be examined. Through MPD the decision maker can be presented the effects of prioritization on the inventory levels of the vehicles based soley on the quantitative environment (delineated by the constraints). The follwing example is presented to illustrate the basic MPD methodology.

<u>Example 3.1</u>

Given: $\max f_1(x) = 5x_1 + 20x_2$

$\max f_2(x) = 23x_1 + 32x_2$

Subject to: $10x_1 + 6x_2 \leq 2500$

$5x_1 + 10x_2 \leq 2000$

$x_1, x_2 \geq 0$

<u>STEP 1</u>: Format the MPD objective function;

$$\max f(\lambda, X) = \lambda_1 f_1 + \lambda_2 f_2$$

$$= (5\lambda_1 + 23\lambda_2)x_1 + (20\lambda_1 + 32\lambda_2)x_2$$

where $\lambda_1, \lambda_2 \geq 0$ and $\lambda_1 + \lambda_2 = 1$

<u>STEP</u> <u>2</u>: Format the initial tableau;

current basis	x_1	x_2	x_3	x_4	RHS	
x_3	10	6	1	0	2500	
x_4	5	10	0	1	2000	
criteria rows	-5	-20	0	0	0	(λ_1)
	-23	-32	0	0	0	(λ_2)

<u>STEP</u> <u>3</u>: Treat one criteria function like a constraint, designate the other criteria function as the zero row and perform MCS (35:499).

<u>STEP</u> <u>4</u>: The following two optimal tableaus (with respect to $f_1(x)$ and $f_2(x)$) result;

x^1 =

current basis	x_1	x_2	x_3	x_4	RHS
x_3	7	0	1	-3/5	1300
x_2	1/2	1	0	1/10	200
criteria rows	5	0	0	2	4000
	-7	0	0	3 1/5	6400
	(Z_1)			(Z_4)	

x^2 =

current basis	x_1	x_2	x_3	x_4	RHS
x_1	1	0	1/7	-3/35	1300/7
x_2	0	1	-1/4	1/7	750/7
criteria rows	0	0	-5/7	17/7	21500/7
	0	0	1	13/5	7700
			(Z_3)	(Z_4)	

STEP 5:

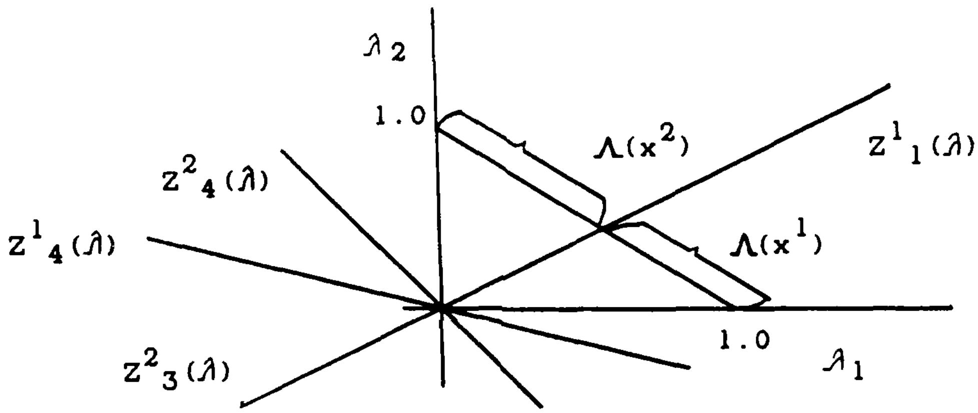
a) The solution of x^1 will stay optimal as long as

$$\left.\begin{aligned} z^1{}_1(\lambda) &= 5\lambda_1 - 7\lambda_2 \geq 0 \\ z^1{}_4(\lambda) &= 2\lambda_1 + 3\ 1/5\lambda_2 \geq 0 \end{aligned}\right\} \text{call this set } \Lambda(x^1)$$

b) The solution of x^2 will stay optimal as long as

$$\left.\begin{aligned} z^2{}_3(\lambda) &= -5/7\lambda_1 + \lambda_2 \geq 0 \\ z^2{}_4(\lambda) &= 17/7\lambda_1 + 13/5\lambda_2 \geq 0 \end{aligned}\right\} \text{call this set } \Lambda(x^2)$$

STEP 6: Graph $\Lambda(x^1)$ and $\Lambda(x^2)$ in the λ_1, λ_2 plane;



STEP 7: The point common to both $\Lambda(x^1)$ and $\Lambda(x^2)$; solve the following system of equations:

$$\begin{aligned} \lambda_1 + \lambda_2 &= 1 \\ 5\lambda_1 - 7\lambda_2 &= 0 \end{aligned} \qquad \text{or} \qquad \begin{aligned} \lambda_1 + \lambda_2 &= 1 \\ -5/7\lambda_1 + \lambda_2 &= 0 \end{aligned}$$

which results in λ_1, λ_2 = (7/12, 5/12)

INTERPRETATION:

a) The N set consists of (0, 200), and (1300/7, 750/7).

b) The optimal prioritization assignment for the two criteria $f_1(x)$ and $f_2(x)$ are 7/12 and 5/12 respectively. Although the priorities are nearly equal, $f_1(x)$, has a higher priority than $f_2(x)$.

The MPD Model

The approach used in this thesis to formulate the MPD model will consist of the following steps: 1) decision variable identification; 2) constraint set identification; 3) identify data necessary to quantify the constraints; 4) formulate the constraints set; and 5) formulate the objective function. A discussion of each of these steps follows.

Decision Variable Identification. The first step in the MPD formulation is to identify the decision variables relevant to the particular HFM acquisition problem. Potentially, all 43 vehicles involved in the HFM program could qualify as decision variables. Although decision variable identification may appear to be straight forward, inconsistencies can surface. For example, suppose the decision maker is soley addressing assault mission vehicles. Although not explicitly stated, the assault "support" vehicles that supply the assault vehicles (ie., ammunition and fuel) must now be included among the decision variables. Careful consideration and feed-back verification from the decision maker concerning the choice of decision variables must take place in this formulation step.

Constraint Identification. The second step in the MPD formulation is to identify the constraints pertaining to the problem of HFM vehicle acquisition. The main objective at this stage of the MPD formulation is to select the minimal

amount of constraints that have a prominent influence on how many of each vehicle type should be acquired and when to acquire these vehicles. As stated in Chapter I, the scope of the methodology is to be designed for an individual to process these questions in a TPIO-HFM office environment. One person could not conveniently process 43 decision variables per fiscal year over a 25 year time line per time related attribute, within a reasonable amount of office time.

The AAMTOR study provides an excellent source of constraints applicable to vehicle acquisition throughout a planning horizon. Table I illustrates which constraints used in in the AAMTOR study can be assessed for the HFM program study.

Table I. Similarity of Problem Constraints

AAMTOR CONSTRAINTS	HFM CONSTRAINTS
BUDGET- procurement, RDT&E, O&M	BUDGET
MISSION- # of vehicles necessary	MISSION
PRODUCTION- capacity per year	PRODUCTION
MIN USE- minimum vehicle service life	
REBUILD- after specified amount of years	
MAX AGE- mandatory retirement	
FLEET AGE- age limit on vehicles performing a mission	
TECHNOLOGY- mandatory levels of the most modern vehicles	TECHNOLOGY
CONTINUOUS PRODUCTION- limit on how long production lines are open	

Data Identification. The third step of the MPD formulation is identifying the data that will quantify the selected constraints. Table II displays applicable data related to each of the constraints to be used in this thesis.

Table II. Data Applicable to Constraints

DATA	CONSTRAINT
RDT&E cost per vehicle type unit production cost per vehicle current vehicle inventory operations and maintenance cost per vehicle	BUDGET
number of missions number of vehicles needed per mission current vehicle inventory	MISSION
number of production facilities production facility capacity production facility operational time line	PRODUCTION
number of high tech vehicles per mission what year is vehicle high tech	TECHNOLOGY

A majority of the applicable data can be obtained from Army Materiel Command (AMC) and the Office of the Deputy Chief of Staff for Operations and Plans (ODCSOPS). Appendix B identifies potential sources for the data illustrated in Table II.

Constraint Set Formulation. The fourth step of the MPD formulation will be the constraint formulation. The decision variables will be represented generically by

$$x_{ic}$$

where i = vehicle type
c = vehicle's cohort year
x = amount of vehicle type i

$$* \; x_{ic} \geq 0$$

For the HFM vehicle types, the cohort year will be the year the vehicle was produced. For the present day heavy force vehicle types (HFM vehicle counterparts) the cohort year is the time line year, because no heavy force vehicle is actually being produced. Hereafter heavy force and present day heavy force are synonomous.

Before the budget, mission, production, and technology constraints are formulated, Table III is presented in order to facilitate referencing indices, technological coefficients, and constants that will be utilized.

Table III. Indices, Technological Coefficients, and Constraint Symbology

INDEX	DEFINITION
i	vehicle type
c	cohort year
t	budget year
TECHNOLOGICAL COEFFICIENT	
O	O&M (Operations and Maintenance) cost/veh
P	Production cost/veh
CONSTANTS	
$BMAX_t$	Annual budget in budget year t
L_t	Lower limit on number of vehicles required for a particular mission in budget year t
U_t	Upper limit on number of vehicles required for a particular mission in budget year t
TN_t	Total quantity of a particular vehicle i in budget year t
$PMAX_t$	Maximum production (number of vehicles) in budget year t
MHT_t	Maximum high tech requirement in budget year t
R_t	Cummulative Research, Developement, Testing, and Evaluation (RDT&E) costs per budget year t

Budget Constraint: The budget constraint includes the following costs: 1) RDT&E costs for HFM vehicle types; 2)production costs for HFM vehicle types; and 3) O&M costs for HFM vehicle costs that have been injected into the inventory, as well as for heavy force vehicle types. Program costs (ie., RDT&E, start-up, operating, and close-out costs with respect to individual production facilities) and "Mothball" costs (cost for retiring a vehicle from the inventory) will not be included in the budget constraint.

The following four assumptions will be used in the budget constraint formulation: 1) all available funds will be spent; therefore, underspending will be ignored; 2) a new vehicle produced will enter the inventory one year after production; 3) once a new vehicle type begins production, RDT&E expenses will not be considered; and 4) foreign military sales negate "mothball" expenses. Figure 7 illustrates an example budget constraint. In this example, the time horizon extends for three years, two heavy force vehicles (x_1 and x_3) and two HFM vehicles (x_2 and x_4) comprise the decision variables.

$$
\begin{array}{lll}
\text{at } t=1: & \Sigma R_1 + Ox_{11} + Ox_{31} & \leq BMAX_{t=1} \\
\text{at } t=2: & Px_{22} + Px_{42} + Ox_{12} + Ox_{32} & \leq BMAX_{t=2} \\
\text{at } t=3: & Px_{23} + Px_{43} + Ox_{13} + Ox_{33} + & \\
 & Ox_{22} + Ox_{42} & \leq BMAX_{T=3}
\end{array}
$$

Figure 7. Example Budget Constraint Set

<u>Mission Constraint</u>. The mission constraint indicates the total number (max and min) of vehicle types necessary for a particular mission's accomplishment. It will be assumed this type information will be available from ODCSOPS (ODCSOPS was the data source for the AAMTOR study). Figure 8 illustrates an example mission constraint. In this example, vehicle types x_1 and x_2 are needed for assault mission accomplishment and vehicle types x_3 and x_4 are needed for assault support mission accomplishment. Notice how the HFM vehicle types do not appear in any

constraint until t=3 (because they were not produced until year t=2, as reflected in the budget constraints).

assault mission:	at t=1:	$x_{11} \geq L_1$
		$x_{11} \leq U_1$
	at t=2:	$x_{12} \geq L_2$
		$x_{12} \leq U_2$
	at t=3:	$x_{13} + x_{22} \geq L_3$
		$x_{13} + x_{22} \leq U_3$
assault support: mission	at t=1:	$x_{31} \geq L_1$
		$x_{31} \leq U_1$
	at t=2:	$x_{32} \geq L_2$
		$x_{32} \leq U_2$
	at t=3:	$x_{33} + x_{42} \geq L_3$
		$x_{33} + x_{42} \leq U_3$

Figure 8. Example Mission Constraint Set

<u>Production Constraint</u>. Production constraints involve HFM vehicle types only. The production constraint example contained in Figure 9 implies the HFM vehicle types x_2 and x_4 require a separate production facility. Although x_1 and x_3 vehicles are not produced because they are already in the inventory, their maximum quantities are accounted for in the 'availability' portion of the production constraint set. Production related data can be obtained from AMC.

For x_2 production	at t=2:	$x_{22} \leq PMAX_2$
	at t=3:	$x_{23} \leq PMAX_3$
For x_4 production	at t=2:	$x_{42} \leq PMAX_2$
	at t=3:	$x_{43} \leq PMAX_3$
For x_1 availability	at t=1:	$x_{11} \leq TN_1$
	at t=2:	$x_{12} \leq TN_2$
	at t=3:	$x_{13} \leq TN_3$
For x_3 availability	at t=1:	$x_{31} \leq TN_1$
	at t=2:	$x_{32} \leq TN_2$
	at t=3:	$x_{33} \leq TN_3$

Figure 9. Example Production Constraint Set

Technology Constraint. The technology constraint forces the HFM vehicle types into the inventory while simultaneously reducing the presence of the older, heavy force vehicle types in the inventory. Notice in the example technology constraint in Figure 10 that the constraints are grouped by specific mission (assault and assault support). Additionally, the time horizon extends from t=3 to t=5 in order to accomodate the two HFM vehicle types (x_1 and x_2) impact on the inventory. It will be assumed that technology data can be obtained from ODCSOPS (which was the source of technology data for the AAMTOR study).

assault mission:	at t=3:	$x_{22} \geq MHT_3$
	at t=4:	$x_{22} + x_{23} \geq MHT_4$
	at t=5:	$x_{22} + x_{23} + x_{24} \geq MHT_5$
assault support mission:	at t=3:	$x_{42} \geq MHT_3$
	at t=4:	$x_{42} + x_{43} \geq MHT_4$
	at t=5:	$x_{42} + x_{43} + x_{44} \geq MHT_5$

Figure 10. Example Technology Constraint Set

Objective Function. The fifth step of the MPD formulation will be the objective function formulation. It is important to reiterate that the objective function is composed of criterion functions. Many possible objective functions can be utilized, the choice of objective function is contingent upon the decision maker's desires. For this thesis research problem, the decision maker desires to obtain some idea of what the priority assignments should be for competing HFM vehicle types. In this case, each criteria will represent specific vehicle type combinations corresponding to a specific mission. If a heavy force vehicle type (referring to vehicle types in the inventory now) has an HFM vehicle type successor (ie., counterpart) then they will both be included in the same criteria function. This stipulation is necessary specifically in the early stages of the time horizon, because the production constriants force a gradual HFM vehicle introduction into the inventory. The gradual HFM vehicle introduction in turn

causes a coexistence of a heavy force vehicle type and its HFM vehicle type successor. Figure 11 illustrates an example objective function formulation that reflects the desire to prioritize the HFM vehicle types (in this case, x_1 and x_3 are the heavy force types and x_2 and x_4 are their HFM vehicle counterparts), over a three year time horizon remembering x_1 and x_2 vehicle types are needed for the assault mission, and x_3 and x_4 vehicle types are needed for the assault support mission).

Objective Function: $\max[\lambda_1 f_1(x) + \lambda_2 f_2(x)]$

where $f_1(x) = x_{11} + x_{12} + x_{11} + x_{22}$ (assault)

$f_2(x) = x_{31} + x_{32} + x_{33} + x_{42}$ (assault spt)

* $\lambda_1 + \lambda_2 = 1$, and $\lambda_1, \lambda_2 \geq 0$

Figure 11. Example Objective Function

Interpretation. Once this MPD problem has been formulated and processed, two prioritization categories will result. One prioritization category will address the prioritization among the missions represented in the objective function by the criterion set (which corresponds to the λ_i values). The second prioritization category will address the prioritization among the vehicle types represented in the objective function. These priorities are determined simply from examining the resulting x_{ic} values and deducing the greater the x_{ic} value, the higher the priority. Thus, the decision maker can be presented with a

table of priority combinations among the different missions (each combination must sum to 1.0) and the corresponding x_{ic} values.

Chapter IV. Illustrative Example and Analysis

The Illustrative Example

This chapter will present the results of processing an illustrative example acquisition problem via the MPD methodology. The illustrative example contains the following attributes: 1) a four year time line (ie., years 1995 - 1998); 2) 4 existing heavy force vehicles will be considered; 3) 4 future HFM vehicles will considered; and 4) the 8 vehicle types necessary for the assault, assault fire support and associated rearm/refuel mission requirements. The objective is to determine how priorities associated with the missions of assault and assault fire support effect the corresponding inventory levels of each vehicle type per year. The illustrative example was processed on the linear optimization software package ADBASE (31), utilizing multiparametric decomposition processing. Appendix C presents a discussion and brief working example of the ADBASE process. Stated here, there are two primary reasons for using this scenario to demonstrate the MPD methodology:

1) The ADBASE software package employed is a demonstration package restricted to process up to 65 constraints and objective functions and 100 structural decision variables. The full-up version of ADBASE can handle any size problem,

limited only by the processing computer's memory capacity (31:12). The illustrative example problem used in this thesis has 50 constraints and objective functions, and 28 structural decision variables.

2) The real world data pertaining to the budget, mission, production and technology constraint sets is classified (30). As depicted in Appendix D (Illustrative Data), the "best available data" was obtained for the categories of unit cost per HFM vehicles, and maximum production of HFM vehicles per year (data only relating to 4 HFM vehicle types). All other data used in the constraints and objective functions is surrogate.

As previously stated the approach used to formulate the illustrative example MPD model appears as: 1) decision variable identification; 2) constraints identification; 3) identification of data necessary to express the constraints; 4) formulation of the constraints; and 5) formulation of the objective function. A discussion of each of these steps follows.

Decision Variable Identification. The following HFM vehicle types are represented: 1) Block III Future Tank (BT); 2) Future Infantry Fighting Vehicle (FIFV); 3) Advanced Field Artillery System (AFAS); and 3) Future Armored Resupply Vehicle (FAR). The following heavy force vehicles (ie., the present day counterparts to the HFM vehicle types)

are portrayed: 1) M1A2 tank; 2) M2A2 infantry vehicle; 3) M109A3 howitzer; and 4) Rearm/Refuel truck (HEM).

Constraint Identification. The following set of constraints will be used to define the alternative space X: 1) budget; 2) mission; 3) production; and 4) technology.

Data Identification. Illustrative data (Appendix D) used in this illustrative example will be a combination of surrogate and open source (ie., obtained from a government agency) data. High tech requirements, force structure levels, budget, and operations and maintenance costs are artificially derived, while production, vehicle unit cost and RDT&E (research, development, testing and evaluation) data are estimates from previous SARDA (Secretary of the Army Research and Development Analysis) studies.

Constraint Formulations. The fourth step of the MPD formulation will be the constraint formulation. The decision variables will be represented by

$$x_{ic},$$

where i = vehicle type
c = vehicle's cohort year
x = amount of vehicle type i

* $x_{ic} \geq 0$

* i=1 =BT
=2 =FIFV
=3 =AFAS
=4 =FAR

HFM VEHICLES

=5 =M1A2
=6 =M2A2
=7 =M109A3
=8 =HEM

HEAVY FORCE VEHICLES

Budget Constraints: The budget constraint equations used in this problem retain the same attributes and assumptions discussed in Chapter III. It is assumed that production for all HFM vehicle types begin in year t=2. The budget constraint set is provided below with the right hand side data in units of millions of dollars. The coefficients in the first budget constraint equation represent the O&M costs of the heavy force vehicles. The coefficients in the remaining equations represent the O&M costs for heavy force and HFM vehicles and HFM vehicle production costs.

1) $.05x_{51} + .01x_{61} + .007x_{71} + .005x_{81} \leq 544.50$ (year t=1)

2) $6.29x_{12} + 4.64x_{22} + 4.95x_{32} + 2.93x_{42} +$
$.05x_{52} + .01x_{62} + .007x_{72} + .005x_{82} \leq 3626.46$ (year t=2)

3) $.03x_{12} + .02x_{22} + .009x_{32} + .008x_{42} +$
$5.0x_{13} + 4.15x_{23} + 4.75x_{33} + 2.83x_{43} +$
$.05x_{53} + .01x_{63} + .007x_{73} + .005x_{83} \leq 4673.90$ (year t=3)

4) $.03x_{12} + .02x_{22} + .009x_{32} + .008x_{42} +$
$.03x_{13} + .02x_{23} + .009x_{33} + .008x_{43} +$
$.05x_{54} + .01x_{64} + .007x_{74} + .005x_{84} \leq 518.30$ (year t=4)

Mission Constraints. The mission constraint set used has all the attributes and assumptions as stated earlier, with the exception that only the minimal amount of vehicle types necessary for a particular mission's

accomplishment need to be considered. In this example, vehicle types x_1, x_2, x_5, and x_6 are needed for assault mission accomplishment. Vehicle types x_3, x_7 are needed for assault fire support and vehicle types x_4, and x_8 are needed for logistics. These mission constraint equations are provided below.

1) $x_{51} + x_{61} \geq 13500$ (lower bound, assault vehicles, t=1)

2) $x_{71} \geq 3500$ (lower bound, assault fire support, t=1)

3) $x_{81} \geq 3500$ (lower bound, logistics, t=1)

4) $x_{52} + x_{62} \geq 13500$ (lower bound, assault vehicles, t=2)

5) $x_{72} \geq 3500$ (lower bound, assault fire support, t=2)

6) $x_{82} \geq 3500$ (lower bound, logistics, t=2)

7) $x_{12} + x_{22} +$
$x_{53} + x_{63} \geq 13370$ (lower bound, assault vehicles, t=3)

8) $x_{32} + x_{73} \geq 3484$ (lower bound, asslt fire spt, t=3)

9) $x_{42} + x_{83} \geq 3554$ (lower bound, logistics, t=3)

10) $x_{12} + x_{22} + x_{13} +$
$x_{23} + x_{54} + x_{64} \geq 13117$ (lower bound, assault, t=4)

11) $x_{32} + x_{33} + x_{74} \geq 3460$ (lower bd, aslt fire spt, t=4)

12) $x_{42} + x_{43} + x_{84} \geq 3460$ (lower bd, logistics, t=4)

Production Constraint. It was assumed that each HFM vehicle type will be produced in a different facility. Although heavy force vehicles are not produced because they are already in the inventory, their minimum quantities will be represented in this example; hence, the

"availability" portion of the constraint set is included. The Production/Availability constraints are as follows:

PRODUCTION:

1) $x_{12} \leq 335$ (max production, BLK III, year t=2)

2) $x_{22} \leq 125$ (max production, FIFV, year t=2)

3) $x_{32} \leq 120$ (max production, AFAS, year t=2)

4) $x_{42} \leq 120$ (max production, FAR, year t=2)

5) $x_{13} \leq 500$ (max production, BLK III, year t=3)

6) $x_{23} \leq 250$ (max production, FIFV, year t=3)

7) $x_{33} \leq 180$ (max production, AFAS, year t=3)

8) $x_{43} \leq 180$ (max production, FAR, year t=3)

9) $x_{14} \leq 500$ (max production, BLK III, year t=4)

10) $x_{24} \leq 250$ (max production, FIFV, year t=4)

11) $x_{34} \leq 180$ (max production, AFAS t=4)

12) $x_{44} \leq 180$ (max production, FAR, year t=4)

AVAILABILITY:

13) $x_{51} \geq 9000$ (lower bound, M1A2, year t=1)

14) $x_{61} \geq 4500$ (lower bound, M2A2, year t=1)

15) $x_{52} \geq 9000$ (lower bound, M1A2, year t=2)

16) $x_{62} \geq 4500$ (lower bound, M2A2, year t=2)

17) $x_{53} \geq 8000$ (lower bound, M1A2, year t=3)

18) $x_{63} \geq 4980$ (lower bound, M2A2, year t=3)

19) $x_{73} \geq 3382$ (lower bound, M109, year t=3)

20) $x_{83} \geq 3452$ (lower bound, HEM, year t=3)

(continued)

21) $x_{54} \geq 8000$ (lower bound, M1A2, year t=4)

22) $x_{64} \geq 4090$ (lower bound, M2A2, year t=4)

23) $x_{74} \geq 3205$ (lower bound, M109, year t=4)

24) $x_{84} \geq 3205$ (lower bound, HEM, year t=4)

Technology Constraints. In this example, individual minimal HFM vehicle type constraints will be implemented. This constraint set includes HFM vehicles with cohort years 2 and 3 because a) production of HFM vehicles does not begin until budget year t=2, and b) the time line only extends out to budget year t=4 (that is, HFM vehicles with cohort year 4 are not included since these vehicles cannot enter the inventory until budget year t=5). The technology constraint set appears as follows:

1) $x_{12} \geq 284$ (min high tech, BLK III, for t=3)

2) $x_{22} \geq 106$ (min high tech, FIFV, for t=3)

3) $x_{32} \geq 102$ (min high tech, AFAS, for t=3)

4) $x_{42} \geq 102$ (min high tech, FAR, for t=3)

5) $x_{13} \geq 425$ (min high tech, BLK III, for t=4)

6) $x_{23} \geq 212$ (min high tech, FIFV, for t=4)

7) $x_{33} \geq 153$ (min high tech, AFAS, for t=4)

8) $x_{43} \geq 153$ (min high tech, FAR, for t=4)

Objective Function. The criteria comprising the objective function will represent the two specific missions, of assault and assault fire support. It is important to notice how logistics is incorporated into both criteria

functions, as opposed to formulating a separate third "logistics" criteria function. It is essential that assault and assault fire support vehicles have logistical vehicles available in order to perform their respective mission. It would be inappropriate to represent these logistical vehicle types in competition against assault and assault fire support vehicle types (which is what a third "logistical" criteria function would represent), when actual dependency exists. It is assumed that 80% of the logistical vehicle types will be apportioned to assault mission vehicle types and 20% will be apportioned to the assault fire support mission vehicle types. The criteria functions and the objective functions are illustrated below. The coefficients in the criteria functions represent the logistical vehicle apportionment between the assault and assault fire support missions.

CRITERIA FUNCTIONS

$$f_1(x) = x_{51} + x_{61} + .8x_{81} + x_{52} + x_{62} + .8x_{82} + x_{53} + x_{12} + x_{63} + x_{22} + .8x_{83} + .8x_{42} + x_{54} + x_{13} + x_{64} + x_{23} + .8x_{84} + .8x_{43}$$

$$f_2(x) = x_{71} + .2x_{81} + x_{72} + .2x_{82} + x_{73} + x_{32} + .2x_{83} + .2x_{42} + x_{74} + x_{33} + .2x_{84} + .2x_{43}$$

OBJECTIVE FUNCTIONS

1) max $(\lambda_1, f_1(x))$ ---assault mission

2) max $(\lambda_2, f_2(x))$ ---assault fire support mission

* $\lambda_1 + \lambda_2 = 1.0$

* $\lambda_1, \lambda_2 \geq 0$

ADBASE Processing

In order to process this example on ADBASE, two input files (referred to as the 'ifi' and 'qfi' files) were created. The ifi file (which is a specialized formatted tableau depicting the constraints, objective functions, and the weighting assignments) and the qfi file (a file specifying which type of solution simplex is desired) are described in Appendix E. Before the results are presented, the issue of 'weighting assignments' will be addressed. As stated in Appendix C, ADBASE software has the ability to 'search' over a specified weighting interval and locate the extreme points on the efficient frontier (the N-set boundary) corresponding to a specific weighting assignment that lies within the prespecified weighting interval. Therefore, after examining a weighting interval, ADBASE will present an extreme point x^i (solution decision variables) and the corresponding convex cone $\Lambda(x^i)$. For each convex cone generated, a corresponding change in direction of the solution space boundary (ie., turning point) takes place. Graphically, this relationship is arbitrarily illustrated in Figure 12.

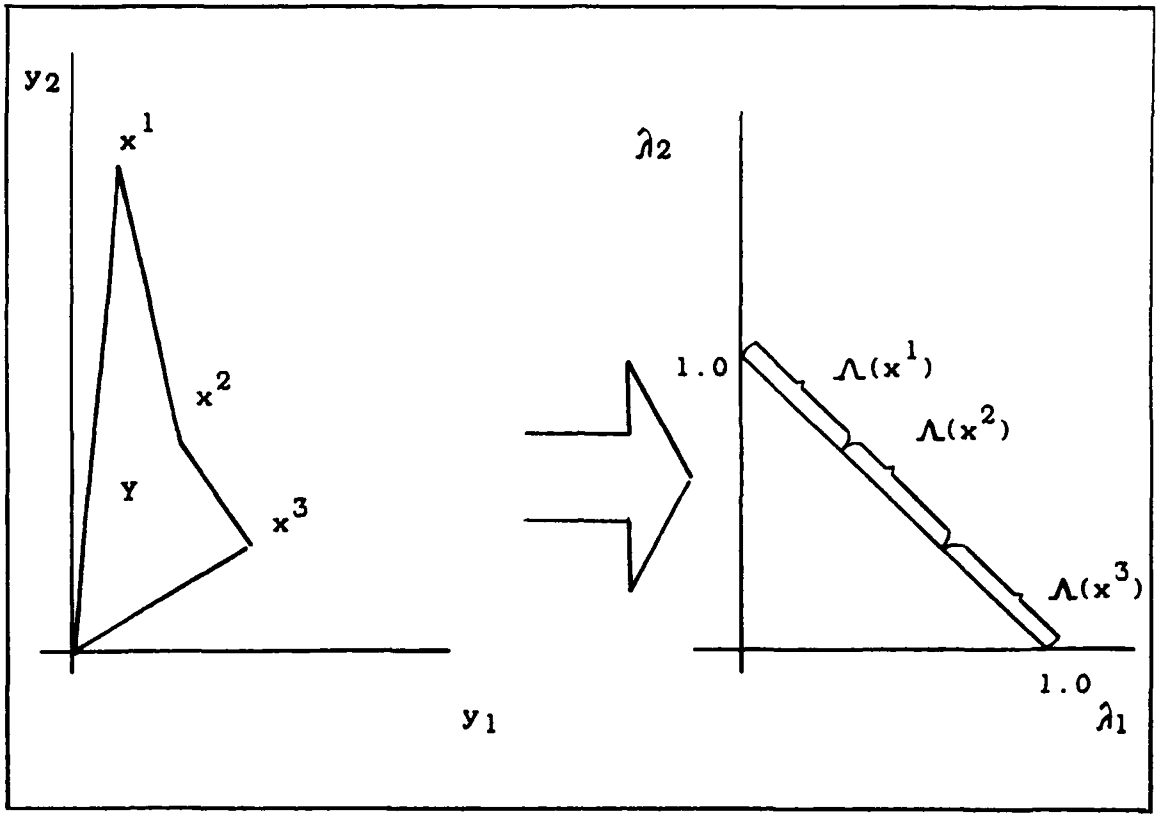


Figure 12. Y Space Relationship with the Convex Cone

The points common to the $\Lambda(x^{i's})$ (reference Chapter III or Appendix C) are the resulting weighting assignments for the criteria functions (in this case, the 2 criteria functions). It is important to remember that the c_j - z_j rows associated with each efficient basis (which contain the x^i) must be examined in order to determine the corresponding weighting assignments. The analyst should consider whether it is more efficient to use the interval search approach among the weighting values (and the c_j - z_j row analysis) or use a fixed weighting assignment approach, obtain the corresponding efficient extreme point, and repeat the

process assigning different weighting values to the criteria functions (ie., iterate).

The Illustrative Example Results

Initially, the illustrative example problem was processed on ADBASE using the interval search approach with respect to the criteria functions' weights. A weighting interval of [.3 to 1.0] was specified for each criteria function, and 9 extreme points ($x^{i's}$) were produced. In lieu of examining the associated $c_j - z_j$ rows and calculating the eventual associated weights, it was determined that the problem could be processed more efficiently by way of the fixed weighting/iterative approach, beginning at $(\lambda_1,\lambda_2) = (.9,.1)$ and iterating by .1 until $(\lambda_1,\lambda_2) = (.1,.9)$. The resulting solution is shown below in Table XI (the actual ADBASE output for both interval and fixed weights approaches are contained in Appendices G and F respectively).

Table XI. Solution of Fixed Weighting Iterations

λ_1	.9	.8	.7	.6	.5	.4	.3	.2	.1
λ_2	.1	.2	.3	.4	.5	.6	.7	.8	.9
(t=1) x51	9000 --------->						9000 --------->		
x61	4500 --------->						4500 --------->		
x71	3500 --------->						4571 --------->		
x81	5000 --------->						3500 --------->		
(t=2) x52	9000 --------->						9000 --------->		
x62	4500 --------->						4500 --------->		
x72	3500 --------->						4571 --------->		
x82	5000 --------->						3500 --------->		
(t=3) x53	8000 --------->						8000 --------->		
x12	284 --------->						284 --------->		
x63	4980 --------->						4980 --------->		
x22	106 --------->						106 --------->		
x73	3382 --------->						4275 --------->		
x32	102 --------->						102 --------->		
x83	4702 --------->						3452 --------->		
x42	102 --------->						102 --------->		
(t=4) x54	8000 --------->						8000 --------->		
x13	425 --------->						425 --------->		
x64	4090 --------->						4090 --------->		
x23	212 --------->						212 --------->		
x74	3205 --------->						4201 --------->		
x33	153 --------->						153 --------->		
x84	4600 --------->						3205 --------->		
x43	153 --------->						153 --------->		
$\max(\lambda_1, f_1(x))$	68742 --------->						64226 --------->		
$\max(\lambda_2, f_2(x))$	17753 --------->						20656 --------->		
	[------- $\Lambda(x^1)$ ---------------]						[-- $\Lambda(x^2)$ ------]		

After reviewing Table XI, the boundaries for the two convex cones can be defined. $\Lambda(x^1)$ results when the $(\lambda_1:\lambda_2)$ interval ranges from [.9:.1] to [.3:.7], and $\Lambda(x^2)$ results when the $(\lambda_1:\lambda_2)$ interval ranges from [.3:.7] to [.1:.9]. Graphically, the solution space and the

associated convex cone plot appear as illustrated in Figure 13.

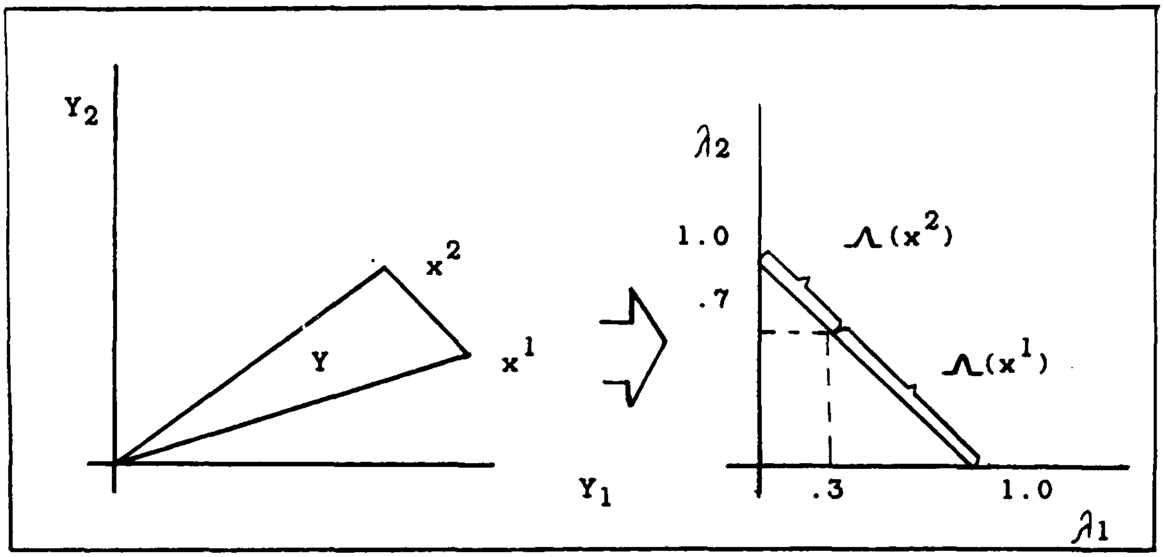


Figure 13. Graphs of the Solution Space and Convex Cones

Analysis

The decision maker can now be presented with a specific weighting factor combination (between λ_1 and λ_2) that diverges when the solution set changes (as illustrated in Figure 13 where the solution space's boundary changes direction from the x^2 point to the x^1 point). In this example, the same vehicle type inventory levels will result when the assault mission is weighted anywhere from 80% higher priority than the assault fire support mission ((ie., $(\lambda_1:\lambda_2)$ = [.9:.1])) down to 20% lower priority than the assault fire support mission ((ie.,$(\lambda_1:\lambda_2)$ = [.4:.6])). For weighting combinations where the assault fire support mission is weighted 40% higher priority than the assault mission ((ie., $(\lambda_1:\lambda_2)$ = [.3:.7])) different inventory levels result with respect to the vehicle types. The inventory levels for each vehicle type do not change when the assault fire support mission's weighting factor is increased over 70%. The decision maker can be provided insight on how the inventory levels of each vehicle type are affected as the prioritization of their associated mission changes. The decision maker can be shown that the ultimate effect of increasing the assault fire support mission's priority over the assault mission's priority is an increase in the inventory levels of howitzer vehicle types, and a decrease in the inventory levels of fueling vehicles. Additionally, these inventory levels will not change until the assault

fire support mission is considered 2.3 times as important as the assault mission.

Reference was made to 9 extreme points being generated when the interval search approach was initially used on this example problem (reference page 51). The 9 extreme points located between the x^1 and x^2 extreme points in solution space will graph as illustrated in Figure 13. Subsequent examination of the $c_j - z_j$ rows associated with the 9 extreme points reveal a more resolved turning point in the solution space compared to the current turning point (which can be expressed as "between the $(\lambda_1:\lambda_2)$ weighting combinations of [.4:.6] and [.3:.7]"). In the context of the example used in this thesis research, the high resolution turning point is not desired by the decision maker; therefore, the turning point resulting from the fixed weighting approach suffices.

Because the HFM vehicle acquisition scenario is linear (reference Chapter I), examination of the investment potential of each resource can be done by analyzing the "shadow prices".

Shadow prices (often referred to as "dual variables") associated with specific resources reveal their (the resources') marginal value. Marginal value refers to the rate at which the objective functions can be increased or decreased by increasing the input of a specific resource by one unit (16:41). By properly constructing the input file

to ADBASE (ie., the qfi file), the final tableau and corresponding $c_j - z_j$ rows can be included in the ADBASE output file (ie., the sfi file). Appendix I contains an ADBASE input file that will cause the final (optimal) tableau and corresponding $c_j - z_j$ rows to be included as part of the output. Table XII summarizes the resulting dual variables and their associated marginal return rates with respect to both objective functions ($f_1(x)$ and $f_2(x)$). The resource numbers in Table XII correspond to the same row numbers as in the vehicle acquisition tableau (Appendix H). The following (λ_1,λ_2) weighting assignments produced unique sets of dual variables: 1) [.9,.1] to [.6,.4]; 2) [.5,.5]; 3) [.4,.6]; and 4) [.3,.7]. Table XII indicates that each dual variable has a different marginal return rate with respect to each objective function.

The dual variables listed above the dotted line in Table XII have a positive marginal return rate on both objective functions' values. Assuming all costs remained the same, the associated resources listed above the dotted line in Table XII would prove profitable if invested into. The dual variables listed below the dotted line each have a "split effect" (ie., a positive and negative return rate) on the two objective functions. If additional investment into a resource whose dual variable indicates a "split effect" is being considered, then the decision maker must determine if the enhancement of one objective function's value is worth

Table XII. Dual Variables Analysis

DUAL VAR ASSOC WITH RESOURCE#:	MARGINAL RATE (OBJ 1/OBJ 2) (.9,.1)-(.6,.4)	(.5,.5)	(.4,.6)	(.3,.7)-(.1,.9)
39 (M1A2; t=2)	(1015/253)	(1015/253)	(1016/254)	(0)
41 (M1A2; t=3)	(805/201)	(805/201)	(805/201)	(0)
40 (M2A2; t=2)	(795/197)	(795/197)	(794/198)	(0)
42 (M2A2; t=3)	(761/189)	(761/189)	(761/189)	(0)
47 (M109; t=4)	(9/2)	(9/2)	(9/2)	(0)
43 (M109; t=3)	(6.4/1.6)	(7/2)	(7/2)	(0)
44 (HEM; t=3)	(6.4/1.6)	(7/2)	(7/2)	(0)
45 (M1A1; t=4)	(6.4/1.6)	(6.4/1.6)	(7/2)	(0)
36 (FAR; t=3)	(.6/.4)	(.6/.4)	(0)	(0)
33 (BLKIII;t=2)	(.6/.4)	(0)	(0)	(0)
....				
48 (HEM; t=4)	(-1.4/.72)	(1.4/-.72)	(1.4/-.72)	(0)
24 (H&F t=3,2)	(-1.4/.72)	(-1.4/.72)	(-1.4/.72)	(0)
35 (AFAS; t=3)	(1.12/-.7)	(1.12/-.7)	(1.12/-.7)	(0)
46 (M2A2; t=4)	(1.12/-.7)	(1.12/-.7)	(1.12/-.7)	(0)
2 (BUDG; t=2)	(-1.12/.7)	(-1.12/.7)	(-1.12/.7)	(0)
5 (BLKIII;t=2)	(-1.12/.7)	(-1.12/.7)	(-1.12/.7)	(0)
22 (HEM; t=2)	(-1.12/.7)	(-1.12/.7)	(0)	(0)
13 (BLKIIIt=4)	(0)	(0)	(0)	(1/-907)
17 (MINASL;t=1)	(0)	(0)	(0)	(1/-709)
45 (M1A2; t=4)	(0)	(0)	(0)	(1/-7)
21 (MINAFS;t=2)	(0)	(0)	(0)	(1/-7)
20 (MINASL;t=2)	(0)	(0)	(0)	(1/-7)
19 (MINLOG;t=1)	(0)	(0)	(0)	(1/-7)
23 (MINASL;t=3)	(0)	(0)	(0)	(1/-7)
47 (M109;t=4)	(0)	(0)	(0)	(1/-7)
3 (BUD;t=3)	(0)	(0)	(0)	(.8/-.5)
34 (FIFV;t=3)	(0)	(0)	(0)	(-.8/.5)
44 (MINHEM;t=3)	(0)	(0)	(0)	(-1/7)
43 (MINM109;=3)	(0)	(0)	(0)	(-1/7)
41 (MINM1A2;=3)	(0)	(0)	(0)	(-1/7)

the degradation of the other objective function's value. If (for example) the AFAS year 3 vehicle is being considered, dual variable analysis reveals investing into the AFAS year 3 resource enhances the first objective function's value but degrades the second objective function's value when the (λ_1, λ_2) weighting assignments range from [.9,.1] to [.4,.6]. The decision maker must then determine if the trade off is worth the investment. If resource costs do not remain constant, then as long as their associated dual variable values remain greater than the unit cost the additional investment into that particular resource is worthwhile (16:42). Table XII also illustrates an important trend that occurs as the priorities between the assault and assault fire support missions change. The number of resources that impact positively on both objective functions decreases as the assault mission's priority decreases. There are 10 resources that impact positively as the assault mission's priority ranges from .9 to .6. When the assault mission's priority decreases to .5, only 9 resources impact positively, and at the .4 priority level only 8 resources impact positively. Once the assault mission's priority drops to .3 and below, no resources impact positively on the objective functions. This trend implies that specific prioritization levels may or may not be conducive to increased resource investment.

The sensitivity of this example can be examined by observing how much the original right hand side values of the constraints can increase or decrease without effecting the current solution. This type of sensitivity analysis is called ranging. Specifically, the basis' inverse and right hand side vector ($\mathbf{B}^{-1}$ and $\mathbf{b}$) are used in the following equation:

$$\mathbf{B}^{-1}\mathbf{b} \geq 0$$

(The vector **b** contains a parameter b_i for each element, and once all the constants are consolidated and transferred to the other side of the inequality the b_i will then indicate either how much of an increase or decrease the specific resource can endure without changing the solution) (16:693). The basis inverse and right hand side vector can be obtained from the final (optimal) tableau.

Although ADBASE can provide the example's final tableau, it does not compute the range of each right hand side value. In this thesis, ranging can be accomplished by the following two methods: 1) substitute the actual $\mathbf{B}^{-1}$ matrix and **b** vector into $\mathbf{B}^{-1} \geq 0$ and solve for **b**; or 2) rerun the problem after varying a resource's value by a certain amount and see if the solution remains the same.

The first method of ranging has the advantage of being able to simultaneously give the allowable increase and decrease of a resource's value (if they exist) without changing the original solution. The analyst, however, must

identify the most restrictive range for each resource after computing 196 vector multiplications ((for the (λ_1, λ_2) = [.9,.1] fixed weighting assignment scenario)). The second method of ranging relies on decision maker input with respect to how much a resource's value may change. Once this input is obtained, the appropriate change is implemented and the problem is rerun. This method will only indicate if the change in the resource's value effects the solution.

The second method of ranging (rerun method) was selected for the example's analysis. The (λ_1,λ_2) = [.9,.1] through [.1,.9] fixed weighting assignments were examined, concentrating on the budget resource (annual budget allotments). Figure 14 illustrates the effects on the solution after varying an annual budget's quantity by small increments of 1%, .5%, and .25%. Three types of "effects" are possible: 1) the solution remains the same; 2) the scenario can still be evaluated; however, the solution changes; and 3) the change in the right hand side value induces an inconsistency in the constraint set, hence the scenario cannot be evaluated (referred to as "infeasible"). The annual budgets' ranges were analyzed one at a time (note that only decreases in budgets were examined). Regardless of weighting assignment, the same effect on the solution resulted.

BUDGET YEAR	EFFECT ON THE SOLUTION WITH A: 1% DECREASE	.5% DECREASE	.25% DECREASE
t=1	CHANGES	CHANGES	CHANGES
t=2	INFEASIBLE	INFEASIBLE	INFEASIBLE
t=3	INFEASIBLE	INFEASIBLE	INFEASIBLE
t=4	CHANGES	CHANGES	CHANGES

Figure 14. Ranging Results of the Budget Resources

As Figure 14 indicates, the example is not very robust when the budget resources are ranged. The t=2 and t=3 budget resources are critically sensitive to small decreases (to such an extent that a feasible solution cannot be obtained). Although a different solution results when either t=1 or t=4 budget resources are decreased, at least a solution can be produced that lies within the accepted alternative space. The analyst can now tell the decision maker the acquisition model is highly sensitive to budget alterations, and major revisions within the constraint sets would be necessary if the second or third year budgets were revised.

Figure 15 shows the ranging results when the minimum high technology requirements (minimum quantities of HFM vehicles that must be injected into the inventory) were ranged (in this case, increases of 1%, .5%, and .25% were examined).

INJECTION YEAR	EFFECT ON THE SOLUTION WITH A: 1% INCREASE	.5% INCREASE	.25% INCREASE
t=3	INFEASIBLE	INFEASIBLE	INFEASIBLE
t=4	INFEASIBLE	INFEASIBLE	INFEASIBLE

Figure 15. Ranging Results of the Minimum High Technology Requirement

The results portrayed in Figure 15 remain the same regardless of mission weighting assignments and vehicle type. This indicates the example is critically sensitive to increases in minimum HFM vehicle inventory levels.

A comparison among the solution decision variables' values and the constraint set should be done in order to to see if any blatant unacceptable inventory levels are being suggested. This "sanity check" may illuminate a major oversight that could have taken place during the problem's formulation and processing.

The results of this example appear to be reasonable; however, if a revised criterion set was processed, there is no guarantee that an acceptable solution would result. Should suspect solutions arise, (ie., appropriate weighting assignments yielding inane results), examination of the correlation between the objective functions may reveal the reason why these solutions are being generated. Steuer describes a metric α that can evaluate the correlation between the objective functions (32:198). The metric α is calculated by the following equation:

$$\alpha = \cos^{-1} \left\{ \frac{(C^i)^T C^j}{\|C^i\| \; \|C^j\|} \right\}$$

where: i and j are the objective functions

$\|C^i\|$ represents the norm of the i vector representing the i objective function

α is an angle

*NOTE: $\|C^i\| = \left(\sum_{j=1}^{n} C^{i2}{}_j \right)^{1/2}$

The smaller the α, the more correlated the objective functions are. The more correlated the objective functions are, the more likelihood that suspect results will be produced (32:198). Should unacceptable solutions result, and subsequent calculation of the correlation metric α result in a small value, then the analyst may want to restructure the objective functions if possible. Generally, a α value between 70 and 90 degrees indicates negligible correlation. A α value between 69 and 50 degrees indicates objective functions' correlation could be a hindrance. Any α value less than 50 degrees indicates correlation will more than likely adversely effect the solution. In the example's case,

$$\alpha = \cos^{-1} \left\{ \frac{(C^1)^T C^2}{\|C^1\| \; \|C^2\|} \right\}$$

α = .96/9.942

α = 84.45 degrees

where C^1 is the vector representing the assault mission objective function

C^2 is the vector representing the assault fire support mission objective function

The large α value is consistent with the conclusion that the results produced in the illustrative example are acceptable.

Chapter V. Findings and Conclusions

The purpose of this thesis research was to develop a quantitative decision aid to augment the subjective assessment prioritization of future vehicle acquisition. Multiparametric decomposition was the methodology selected to model this acquisition scenario and render specific inventory levels for all vehicles as future vehicles (HFM) are injected into the inventory.

Findings

Resulting Inventory Multiparametric Decomposition incorporating a mission oriented approach produced the following inventory (for a 4 year time horizon with 4 present day vehicles and 4 future vehicles):

	YEAR			
VEHICLES	1	2	3	4
[OLD]				
M1A2	9000:9000	9000:9000	8000:8000	8000:8000
M2A2	4500:4500	4500:4500	4980:4980	4090:4090
M109	3500:4571	3500:4571	3382:4275	3205:4201
HEM	5000:3500	5000:3500	4702:3452	4600:3205
[FUTURE]				
BLK III	N/A	N/A	284: 284	425: 425
FIFV	N/A	N/A	106: 106	212: 212
AFAS	N/A	N/A	102: 102	153: 153
FAR	N/A	N/A	102: 102	153: 153

*NOTE: for the aaaa:bbbb quantities, aaaa quantity results from a assault to assault fire support mission priority interval of [.9,.1] to [.4,.6]. The bbbb quantity results from a priority interval of [.3,.7] to [.1,.9].

ADBASE software (a multiobjective linear optimization package) was used to process the MPD methodology for the example problem. A Zenith 248 personal computer processed the example problem in 6.75 minutes when the ADBASE fixed weights/iterations approach was used (ie., 45 seconds per iteration). When the ADBASE interval search approach was used, the problem was processed in 7.01 minutes.

Data Obtaining data necessary to illustrate the MPD application on the vehicle acquisition scenario was extremely difficult. Admittingly, there is more surrogate data used in the illustrative example than originally planned and desired. A majority of the key data is either classified or still being developed in the ongoing HFM economic analysis study (30). Regardless of the source of the data, the analyst must be prepared to take action if the data being used causes inconsistent constraints with respect to the corresponding multiobjective linear problem. With a constraint set and objective function set as large as the one that comprised the illustrative example's tableau, it can be very common for inconspicuous inconsistencies to plague the subsequent processing (which did occur). One remedy for rectifying inconsistent constraints is to "track" down the cause (which is usually due to right hand side values) and make appropriate revisions. In the illustrative example's case, one constraint at a time was deleted from the tableau, and processing was attempted. If

the tableau was processed, the deleted constraint was identified as inconsistent. Once all the inconsistent constraints were identified, their associated right hand side values were examined individually. Specifically, the right hand side values were altered (by small increments) and the tableau was reprocessed. This 'brute force' method was continued until feasibility was obtained.

<u>Factor Aggregation</u> The budget constraint equation set used in this example was simplified, aggregating a number of factors into one term. Thorough factor by factor data would have required a much more intensive analysis, which was not the purpose of this thesis. For example, the O&M cost data should include (minimally) the following expenses per vehicle type: 1) fuel and lubricants; 2) repair parts; 3) related test equipment; 4) mechanic's specialty training; 5) major end items; and 6) ammunition. This listing of expenses is by no means exhaustive, the intent is to merely illuminate how large the tractability of just the O&M costs can become.

Another simplification was employed in the area of logistical vehicle apportionment. As is the case with O&M costs, a separate analysis would have had to be conducted in order to determine logistical vehicle apportionment for each of the supported vehicle types. As an example, logistical vehicle apportionment could have been based on fuel and ammunition consumption. In the case of tanks and

infantry, the (assault mission) vehicles consume more fuel than howitzers in their assault fire support mission; however, howitzers consume more ammunition than tanks and infantry vehicles. A further complication in the analysis could occur when one logistical vehicle is used for both rearming and refueling. From this example, one can surmise that the logistical vehicle apportionment issue is not a simple problem.

Value Function Design The example problem contains linear objective functions, inferring the value of each mission can simply be expressed as the sum of each vehicle's resulting inventory level. This "additive value function" representation of each mission (objective function) connotes an independent relationship among the variables that comprise the objective functions (8). If an independent relationship exist among the variables, one need not consider how the variables effect each other.

The synergism between vehicles within a mission might be portrayed more realistically via a multiplicative value function. A multiplicative relationship can portray a more profound synergistic relationship among the decision variables than a linear (additive) value function. For example, instead of one tank and one infantry vehicle portraying an assault mission value of 2 (for an additive value function), a decision maker may consider this combined armor/infantry mix more effective. The enhanced mission's

value may actually be 10 (which can be expressed by a nonlinear or multiplicative value function). MPD can still be applied to the acquisition environment if nonlinear objective functions are incorporated; however, the constraint set will have to maintain linearity. To date, nonlinear value functions have not been implemented in vehicle acquisition models. Capturing a more realistic synergistic relationship among vehicles within a mission by way of a nonlinear (multiplicative) value function is an area of research that could greatly enhance the MPD acquisition approach developed in this thesis.

Block Diagonal Structure When the example's tableau (reference appendix H) is rearranged, a block diagonal structure of the constraint set will result. This block diagonal structure facilitates exploiting the potential insights associated with decomposition principles (2:305). Decomposition principles concentrate primarily on the relationship between the subproblems' (blocks within the tableau) optimal solutions and the overall (global) optimum (2:306). This relationship could offer a powerful insight into how an efficient solution is determined in the vehicle acquisition process. Potentially, a specific diagonal block's optima could be identified as the "strongest influence" on the global optimum. The decision makers would then be able to focus on the allocation of a subset of the resources (corresponding to the strongest influencing

block) instead of examining the entire resource set, allowing a more efficient decision making process. How the strongest influencing diagonal blocks are identified from an acquisition tableau is a topic requiring further research.

Conclusions

A common inclination when modeling vehicle acquisition is to conceptualize individual vehicles entering the inventory based on a prioritization process. This "prioritization of individual vehicles" approach has two deficiencies: 1) If available, the force structure data will implicitly reflect the prioritization among each vehicle; and 2) this approach contradicts the "combined arms" tactics inherent in the AirLand Battle-Future warfighting doctrine. The former deficiency implies initiating a study even though the information sought is already available. The latter deficiency implies modernizing the inventory based on an individual basis even though success on the battlefield depends on the synergism produced by a specific group of different vehicle types performing a particular mission.

This thesis has produced a unique approach towards modeling future vehicle acquisition. In lieu of prioritizing individual vehicles, this thesis has developed a methodology that determines the inventory of U.S. Army vehicles based on how specific missions are prioritized with respect to each other. This thesis' acquisition methodology has three advantages that make it superior to the

"prioritization of individual vehicles": 1) the synergistic effect of logistical and weapon systems inherent to each mission is portrayed; 2) the realization of combined arms tactics is facilitated because this methodology produces inventory levels which considers the entire group of vehicles necessary for a mission's accomplishment; and 3) this methodology supports the tenants of the AirLand Battle-Future warfighting concept.

Subjective analysis will inevitably occur when vehicle acquisition policies are to be decided on. With this aspect in mind, the additional advantage of a less controversial subjective analysis surfaces as a result of this thesis' methodology. The prioritization of individual vehicle approach forces decision makers to deliberate on a list that contains as many elements as there are vehicles. On the other hand, this thesis approach only requires that the decision makers deliberate on a mission prioritization list, a list much smaller and less complex than the individual vehicle prioritization list. The less complex potential solutions are, the easier (hence less controversial) the decision making process will be.

Overall, this thesis research has strived for clarity, logical formulations and acceptable assumptions in an effort to procure creditability on the basis of face value validation. This thesis has produced a quantitative vehicle acquisition methodology that supports the U.S. Army

warfighting doctrine, and enhances the subjective acquisition decision making process.

Appendix A: HFM Vehicle Types and Heavy Force Vehicle Counterparts

HFM VEHICLE	DESCRIPTION	HEAVY FORCE COUNTERPART
RV	(Recovery Vehicle)	M88A1
MARS	(Maintenance & Repair System)	M113A2
FC2V	(Future Command & Control Vehicle)	M577A2
FARV	(Future Armored Resupply Vehicle)	FAASV
FRV	(Future Recon Vehicle)	M3A1
AA	(Armored Ambulance)	M113A2
MWS	(Mortar Weapon System)	M106A2
NLOS	(Non-Line of Sight Air Defense/ Anti-Tank System)	NONE
ABAS	(Armored Battalion Aid Station)	M577A2
FACS	(Future Armored Combat System--Tank)	M1A1
FIFV	(Future Infantry Fighting Vehicle)	M2A1
SAPPER	(Engineer Squad Vehicle)	M113A2
AFAS-C	(Advanced Field Artillery System)	M109A3
FSCOLS	(Fire Support Combat Observation Lasing System)	FIST-V
CMV	(Combat Mobility Vehicle)	CEV
LOSAD	(Line of Sight Air Defense)	VULCAN
LOSAT	(Line of Sight Anti-Tank)	ITV
CGC	(Combat Gap Crosser)	AVLB
RAMS	(Rocket & Missile System)	MLRS
NBCRS	(NBC Recon System)	NONE
IEWV	(Intelligence & Electronic Warfare Vehicle)	M1015
CSSV	(Cbt Spt Smoke Vehicle)	M1059
DEW	(Directed Energy Weapon)	NONE
CGV	(Command Group Vehicle)	M577A2

Appendix B: Data Sources

DATA	SOURCE
Budget	Office of the Deputy Chief of Staff for Operations and Plans (ODCSOPS)
Unit production cost for Heavy Force Vehicles	Cost Evaluation and Analysis Center (CEAC)
Unit production cost for HFM vehicles	Army Material Command (AMC)
RDT&E HFM vehicles	AMC
Heavy Force vehicle inventory	AMC, ODCSOPS
HFM Vehicle inventory	AMC, ODCSOPS
Number of Vehicles/ Mission	ODCSOPS
High Tech requirements	ODCSOPS
Production Line Figures	AMC

Appendix C: How ADBASE WORKS

The following sample problem was processed on ADBASE in order to acquire sufficient proficiency in using ADBASE (that will allow the vehicle acquisition problem to be processed):

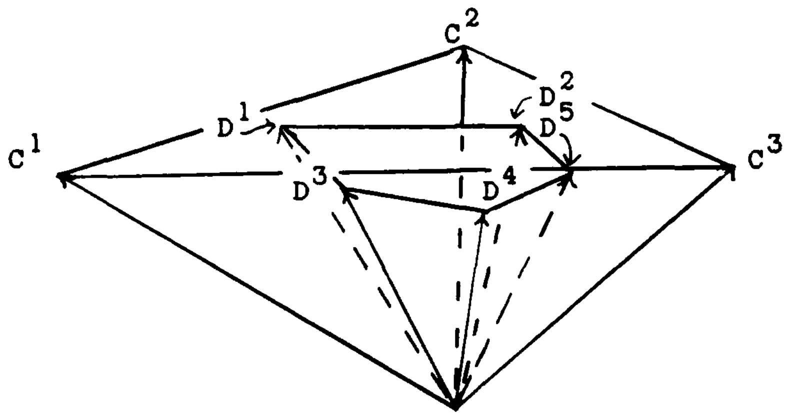
$$
\begin{aligned}
\max\ f_1(\lambda, x) &= \lambda_1(5x_1 + 20x_2) \\
\max\ f_2(\lambda, x) &= \lambda_2(23x_1 + 32x_2) \\
\text{subject to}\quad & 10x_1 + 6x_2 \leq 2500 \\
& 5x_1 + 10x_2 \leq 2000
\end{aligned}
$$

Before reviewing the solutions resulting from the ADBASE processing, some important factors will be presented that aid in the understanding of how ADBASE processes an MPD problem. Depending on how much information the decision maker (DM) has available (ie.,the value of each λ_i), the following "interval criterion weights continuum" results (32:246):

REGULAR VECTOR-MAX PROBLEMS	←	INTERVAL CRITERION WEIGHTS PROBLEMS	→	WEIGHTED-SUMS PROBLEMS
(no knowledge---		unstructured preferences--		specific preferences)

Steuer points out that "...since the interval criterion weights problem involves, in general, an infinite number of weighted-sums problems, it cannot be solved as stated" (32:246). Therefore, in order to overcome the dilemma of having a problem located in the middle of the interval criterion weights continuum, ADBASE transforms this type of

problem into an "interval criterion weights vector-max problem" (32:247). This transformation results in an examination of a subset of the regular criterion cone **C** (from $\{Cx = z | x \quad S\}$). The subset of the criterion cone is called the interval criterion weights cone, symbolized by **D**. The **D** and **C** cones' relationship is illustrated as follows:



The **C** cone matrix is transformed into a **D** cone matrix by

$$\mathbf{D} = \mathbf{TC}$$

where the **T** matrix is referred to as a premultiplication matrix (32:249). The **T** matrix is composed of "critical weights vectors". ADBASE examines a convex combination weighting vector (specified by the user in the form of upper and lower bounds for each λ_i), that when applied to the **C** cone generators, specifies the **D** cone generators (pages 247-249 in reference [32] show in detail how the **D** cone generators are calculated). The convex combination weighting vectors are called the critical weights vectors. With a critical weighting vector for each generator of the

interval criterion weights cone, the **D** cone matrix can be constructed (32:247). Once the **D** cone matrix has been determined, ADBASE then applies a certain type of Multi Criteria (MC) Simplex algorithm to determine the efficient extreme points in the solution space. From the tableaus corresponding to each efficient extreme point, the precise $\hat{\lambda}_i$ values can be determined.

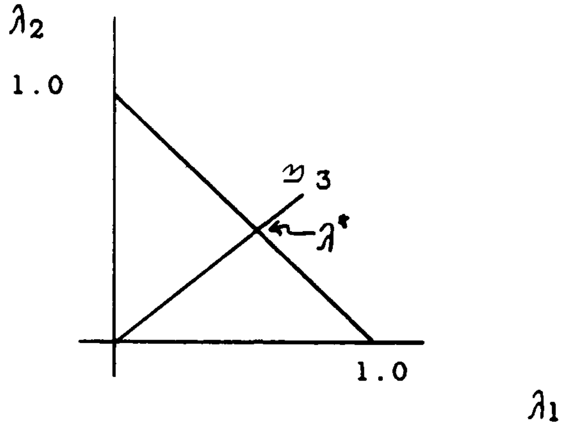
Referring back to the example problem, the next page shows how the problem is read in by ADBASE.

```
*********1*********2*********3*********4*********5*********6*********7**
          1. NUMB..........        1
          2. MODE.........         1
          3. IFASE2........        4
          4. IFASE3........        2
          5. IWEAK.........        0
          6. MLISTB........     2000
          7. IZFMT.........        3
          8. IPRINT(1).....        1
          9. IPRINT(2).....        1
         10. IPRINT(3).....        3
         11. IPRINT(4).....        1
         12. IPRINT(5).....        0
         13. IPRINT(6).....        0
         14. IPRINT(7).....        0
         15. IPRINT(8).....        1
         16. IPRINT(9).....        2
         17. IPRINT(10)....        0
         18. IPRINT(11)....        1
         19. IV9L..........        1
         20. IV9U..........       10
         21. I9L...........        0
-- More --
-- More --

         22. I9U...........     9999
         23. I10L..........        0
         24. I10U..........        0

*********1*********2*********3*********4*********5*********6*********7**
A(  1,  1) =     10.000000
A(  1,  2) =      6.000000
A(  2,  1) =      5.000000
A(  2,  2) =     10.000000

B(  1) =  2500.000000
B(  2) =  2000.000000

C(  1,  1) =      5.000000
C(  1,  2) =     20.000000
C(  2,  1) =     23.000000
C(  2,  2) =     32.000000

WRANGE( 1.1) =      .200000      WRANGE( 1.2) =      1.000000       1
WRANGE( 2.1) =      .200000      WRANGE( 2.2) =      1.000000       1

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .8000   .2000
   .2000   .8000

                    2 REDUCED CRITERION CONE GENERATORS
-- More -
```

The next page shows ADBASE output. An interval of [.3 to 1.0] for both criterion weights were examined, resulting in the **T** matrix, as shown. ADBASE then computed **D** = **TC**, then applied its version of MC Simplex. The two efficient extreme points result, as indicated on the printout.

```
                                                              ALL
BASIS          CRITERION VALUES                  BASIC VARIABLE VALUES

  1       Z( 1) =      3071.428571          X(  1) =       185.714286
          Z( 2) =      7700.000000          X(  2) =       107.142857

   TABLEAU WITH C(J)-Z(J) REDUCED COSTS
          3              4
   ------------------------------------------------------------------
      .14286        -.08571
    -.07143          .14286
   ------------------------------------------------------------------
      .71429       -2.42857
    -1.00000       -2.60000
   ------------------------------------------------------------------

  2       Z( 1) =      4000.000000          X(  3) =      1300.000000
          Z( 2) =      6400.000000          X(  2) =       200.000000

-- More --
-- More --

   TABLEAU WITH C(J)-Z(J) REDUCED COSTS
          1              4
   ------------------------------------------------------------------
     7.00000        -.60000
      .50000         .10000
   ------------------------------------------------------------------
    -1.40000       -2.00000
     3.40000       -3.20000
   ------------------------------------------------------------------

NUMBER OF COMPUTED EFFICIENT BASES             =    2
NUMBER OF EFFICIENT EXTREME POINTS             =    2
NUMBER OF UNBOUNDED EFFICIENT EDGES            =    0

*********1*********2*********3*********4*********5*********6*********7**

                              ADBASE
                          (RELEASE:  9/89)

              A VECTOR-MAXIMUM ALGORITHM FOR GENERATING
        EFFICIENT EXTREME POINTS AND UNBOUNDED EFFICIENT EDGES

-- More --
```

From the efficient bases, the optimal criterion weights can be determined by plotting each solutions' convex cone components (ie., plot v_1, v_2, v_3, v_4 depicted on the previous page) on the following graph:



In this example problem, the v_3 component is the only component that intersects the line segment connecting (1.0, 0) and (0, 1.0). The point of intersection, λ^*, represents the optimal criterion weights. λ^* can be calculated by solving the following system of equations:

$$\lambda_1 + \lambda_2 = 1$$

$$.71429\lambda_1 - \lambda_2 = 0 \qquad (v_3)$$

λ^* calculates to (.58, .42).

Appendix D: Illustrative Data

Table IV. Maximum Annual Budget

YEAR	AMOUNT (MILLIONS $)
1995	544.50
1996	3626.46
1997	4673.90
1998	518.30*

SOURCE: SURROGATE

*NOTE: The 1998 budget may appear too low; however, only O&M costs need to be accounted for in year t=4 (1998) because of the assumption that states a newly produced HFM vehicle produced in year t=i may not enter the inventory until year t=i+1. Essentially HFM vehicle types with cohort year c=4 do not need to be considered in this four year time horizon because of the 'delayed entry' assumption. If production costs for HFM vehicles c=4 were included in the budget at t=4, the MC-Simplex processing would interpret the production costs as additional O&M moneys and eventually recommend a ridiculously high amount of heavy force vehicles (specifically the least expensive vehicle type to maintain) to be included in the inventory. Similar budge⁺ adjusting was done in years t=2 and t=3, but the adjustment was not as drastic as was done in year t=4.

Table V. Maximum Annual HFM Vehicle Production

VEHICLE	1995	1996	1997	1998
BLK III	0	335	500	500
FIFV	0	125	250	250
AFAS	0	120	180	180
FAR	0	120	180	180

SOURCE: SARDA

Table VI. HFM Vehicle Unit Cost (MILLIONS $)

VEHICLE	1996	1997	1998
BLK III	6.29	5.0	4.8
FIFV	4.64	4.15	4.39
AFAS	4.95	4.75	4.62
FAR	2.93	2.83	2.74

SOURCE: SARDA

Table VII. O&M Costs Per Vehicles (MILLIONS $)

VEHICLE	1995	1996	1997	1998
BLK III	N/A	N/A	.03	.03
M1A2	.05	.05	.05	.05
FIFV	N/A	N/A	.02	.02
M2A2	.01	.01	.01	.01
AFAS	N/A	N/A	.009	.009
M109	.007	.007	.007	.007
FAR	N/A	N/A	.008	.008
HEM	.005	.005	.005	.005

SOURCE: SURROGATE

Table VIII. Minimum High Tech Requirements

VEHICLE	1997	1998
BLK III	284	425
FIFV	106	212
AFAS	102	153
FAR	102	153

SOURCE: SURROGATE

Table IX. Minimum Force Structure Requirements
(# of Vehicles)

MISSION	1995	1996	1997	1998
ASSAULT	13500	13500	13370	13117
AST F S	3500	3500	3484	3460
LOGIST	3500	3500	3554	3460

SOURCE: SURROGATE

Table X. Minimum Amount of Heavy Force Vehicles Required Annually

VEHICLE	1995	1996	1997	1998
M1A2	9000	9000	8000	8000
M2A2	4500	4500	4980	4090
M109	3500	3500	3382	3205
HEM	3500	3500	3452	3205

SOURCE: SURROGATE

Appendix E: ADBASE Input Files (ifi and qfi)

(Go on to next page).

```
 1. NUMB              1

 2. MODE              1

 3. IFASE2            4
 4. IFASE3            2
 5. IWEAK             0

 6. MLSTB          2000
 7. IZFMT             3

 8. IPRINT(1)         1
 9. IPRINT(2)         1
10. IPRINT(3)         3
11. IPRINT(4)         1
12. IPRINT(5)         0
13. IPRINT(6)         0
14. IPRINT(7)         0
15. IPRINT(8)         1
16. IPRINT(9)         2
17. IPRINT(10)        0
18. IPRINT(11)        1
-- More --

 6. MLSTB          2000
 7. IZFMT             3

 8. IPRINT(1)         1
 9. IPRINT(2)         1
10. IPRINT(3)         3
11. IPRINT(4)         1
12. IPRINT(5)         0
13. IPRINT(6)         0
14. IPRINT(7)         0
15. IPRINT(8)         1
16. IPRINT(9)         2
17. IPRINT(10)        0
18. IPRINT(11)        1



-- More --

19. IV9L              1
20. IV9U           9999
21. I9L               1
22. I9U            9999
23. I10L              0
24. I10U              0
```

```
Vehicle acquisition priority
   2010       2      28       15        0       32        1        40
     52
 1  1        .05   1   2        .01   1   3      .007   1   4      .005
 2  5       6.29   2   6       4.64   2   7      4.95   2   8      2.93
 2  9        .05   2  10        .01   2  11      .007   2  12      .005
 3  5        .03   3   6        .02   3   7      .009   3   8      .008
 3 13        5.0   3  14       4.15   3  15      4.75   3  16      2.83
 3 17        .05   3  18        .01   3  19      .007   3  20      .005
 4  5        .03   4   6        .02   4   7      .009   4   8      .008
 4 13        .03   4  14        .02   4  15      .009   4  16      .008
 4 21       4.80   4  22       4.39   4  23      4.62   4  24      2.74
 4 25        .05   4  26        .01   4  27      .007   4  28      .005
 5  5        1.0   6   6        1.0   7   7       1.0   8   8       1.0
 9 13        1.0  10  14        1.0  11  15       1.0  12  16       1.0
13 21        1.0  14  22        1.0  15  23       1.0  16  24       1.0
     16
 1        544.50   2       3626.460   3       4673.90   4         518.30
 5         335.0   6          125.0   7         120.0   8         120.0
 9         500.0  10          250.0  11         180.0  12         180.0
13         500.0  14          250.0  15         180.0  16         180.0
      0
      0
  ..
     48
 1  1        1.0   1   2        1.0   2   3       1.0   3   4       1.0
 4  9        1.0   4  10        1.0   5  11       1.0   6  12       1.0
 7  5        1.0   7   6        1.0   7  17       1.0   7  18       1.0
 8  7        1.0   8  19        1.0   9   8       1.0   9  20       1.0
10  5        1.0  10   6        1.0  10  13       1.0  10  14       1.0
10 25        1.0  10  26        1.0  11   7       1.0  11  15       1.0
11 27        1.0  12   8        1.0  12  16       1.0  12  28       1.0
13  5        1.0  14   6        1.0  15   7       1.0  16   8       1.0
17 13        1.0  18  14        1.0  19  15       1.0  20  16       1.0
21  1        1.0  22   2        1.0  23   9       1.0  24  10       1.0
25 17        1.0  26  18        1.0  27  19       1.0  28  20       1.0
29 25        1.0  30  26        1.0  31  27       1.0  32  28       1.0
     32
 1       13500.0   2         3500.0   3        3500.0   4       13500.0
 5        3500.0   6         3500.0   7       13370.0   8        3484.0
 9        3554.0  10        13117.0  11        3460.0  12        3460.0
13         284.0  14          106.0  15         102.0  16         102.0
17         425.0  18          212.0  19         153.0  20         153.0
21        9000.0  22         4500.0  23        9000.0  24        4500.0
25        8000.0  26         4980.0  27        3382.0  28        3452.0
29        8000.0  30         4090.0  31        3205.0  32        3205.0
-- More --
29 25        1.0  30  26        1.0  31  27       1.0  32  28       1.0
     32
 1       13500.0   2         3500.0   3        3500.0   4       13500.0
 5        3500.0   6         3500.0   7       13370.0   8        3484.0
 9        3554.0  10        13117.0  11        3460.0  12        3460.0
13         284.0  14          106.0  15         102.0  16         102.0
17         425.0  18          212.0  19         153.0  20         153.0
21        9000.0  22         4500.0  23        9000.0  24        4500.0
25        8000.0  26         4980.0  27        3382.0  28        3452.0
29        8000.0  30         4090.0  31        3205.0  32        3205.0
-- More --

     30
 1  1        1.0   1   2        1.0   1   4       .80   1   5       1.0
 1  6        1.0   1   8        .80   1   9       1.0   1  10       1.0
 1 12        .80   1  13        1.0   1  14       1.0   1  16       .80
 1 17        1.0   1  18        1.0   1  20       .80   1  25       1.0
 1 26        1.0   1  28        1.0   2   3       1.0   2   4       .20
 2  7        1.0   2   8        .20   2  11       1.0   2  12       .20
 2 15        1.0   2  16        .20   2  19       1.0   2  20       .20
 2 27        1.0   2  28        .20
      0
      1         .90          .90      1
      2         .10          .10      1
```

Appendix F: Fixed Weighting Assignment Solution Results in ADBASE Output Format

(Go on to next page).

```
WRANGE( 1,1) =       .900000      WRANGE( 1,2) =       .900000       1
WRANGE( 2,1) =       .100000      WRANGE( 2,2) =       .100000       1

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .9000    .1000

                        1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                  BASIC VARIABLE VALUES

    1       Z( 1) =     68742.920000          X(  1) =      9000.000000
            Z( 2) =     17753.480000          X(  2) =      4500.000000
                                              X(  3) =      3500.000000
                                              X(  4) =      5000.000000
                                              X(  5) =       284.000000
                                              X(  6) =       106.000000
                                              X(  7) =       102.000000
                                              X(  8) =       102.000000
                                              X(  9) =      9000.000000
                                              X( 10) =      4500.000000
                                              X( 11) =      3500.000000
                                              X( 12) =      5000.000000
                                              X( 13) =       425.000000
                                              X( 14) =       212.000000
                                              X( 15) =       153.000000
                                              X( 16) =       153.000000
                                              X( 17) =      8000.000000
                                              X( 18) =      4980.000000
                                              X( 19) =      3382.000000
                                              X( 20) =      4702.400000
                                              X( 25) =      8000.000000
                                              X( 26) =      4090.000000
                                              X( 27) =      3205.000000
                                              X( 28) =      4600.000000
```

```
WRANGE( 1,1) =        .800000        WRANGE( 1,2) =        .800000
WRANGE( 2,1) =        .200000        WRANGE( 2,2) =        .200000

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .8000    .2000

                 1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                 BASIC VARIABLE VALUES

    1       Z( 1) =      68742.920000          X(  1) =      9000.000000
            Z( 2) =      17753.480000          X(  2) =      4500.000000
                                               X(  3) =      3500.000000
                                               X(  4) =      5000.000000
                                               X(  5) =       284.000000
                                               X(  6) =       106.000000

                                               X(  7) =       102.000000
                                               X(  8) =       102.000000
                                               X(  9) =      9000.000000
                                               X( 10) =      4500.000000
                                               X( 11) =      3500.000000
                                               X( 12) =      5000.000000
                                               X( 13) =       425.000000
                                               X( 14) =       212.000000
                                               X( 15) =       153.000000
                                               X( 16) =       153.000000
                                               X( 17) =      8000.000000
                                               X( 18) =      4980.000000
                                               X( 19) =      3382.000000
-- More --                                     X( 20) =      4702.400000
-- More --

                                               X( 25) =      8000.000000
                                               X( 26) =      4090.000000
                                               X( 27) =      3205.000000
                                               X( 28) =      4600.000000
```

```
WRANGE( 1,1) =        .700000     WRANGE( 1,2) =        .700000
WRANGE( 2,1) =        .300000     WRANGE( 2,2) =        .300000

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)


   .7000    .3000

                        1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

  BASIS           CRITERION VALUES                  BASIC VARIABLE VALUES

     1        Z( 1) =     68742.920000          X(  1) =      9000.000000
              Z( 2) =     17753.480000          X(  2) =      4500.000000
                                                X(  3) =      3500.000000
                                                X(  4) =      5000.000000
                                                X(  5) =       284 000000
                                                X(  6) =       106.000000
                                                X(  7) =       102.000000
                                                X(  8) =       102.000000
                                                X(  9) =      9000.000000
                                                X( 10) =      4500.000000
                                                X( 11) =      3500.000000
                                                X( 12) =      5000.000000
                                                X( 13) =       425.000000
                                                X( 14) =       212.000000
                                                X( 15) =       153.000000
                                                X( 16) =       153.000000
                                                X( 17) =      8000.000000
                                                X( 18) =      4980.000000
                                                X( 19) =      3382.000000
                                                X( 20) =      4702.400000
-- More --
-- More --

                                                X( 25) =      8000.000000
                                                X( 26) =      4090.000000
                                                X( 27) =      3205.000000
                                                X( 28) =      4600.000000
```

```
WRANGE( 1,1) =     .600000     WRANGE( 1,2) =     .600000     1
WRANGE( 2,1) =     .400000     WRANGE( 2,2) =     .400000     1

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

  .6000   .4000

                    1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                BASIC VARIABLE VALUES

   1       Z( 1) =    68742.920000          X(  1) =     9000.000000
           Z( 2) =    17753.480000          X(  2) =     4500.000000
                                            X(  3) =     3500.000000
                                            X(  4) =     5000.000000
                                            X(  5) =      284.000000
                                            X(  6) =      106.000000
                                            X(  7) =      102.000000
                                            X(  8) =      102.000000
                                            X(  9) =     9000.000000
                                            X( 10) =     4500.000000
                                            X( 11) =     3500.000000
                                            X( 12) =     5000.000000
                                            X( 13) =      425.000000
                                            X( 14) =      212.000000
                                            X( 15) =      153.000000
                                            X( 16) =      153.000000
                                            X( 17) =     8000.000000
                                            X( 18) =     4980.000000
                                            X( 19) =     3382.000000
                                            X( 20) =     4702.400000
-- More --
                                            X( 20) =     4702.400000
-- More --

                                            X( 25) =     8000.000000
                                            X( 26) =     4090.000000
                                            X( 27) =     3205.000000
                                            X( 28) =     4600.000000
```

```
WRANGE( 1,1) =       .500000      WRANGE( 1,2) =       .500000
WRANGE( 2,1) =       .500000      WRANGE( 2,2) =       .500000

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .5000    .5000

                        1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                  BASIC VARIABLE VALUES

   1        Z( 1) =     68742.920000            X(  1) =      9000.000000
            Z( 2) =     17753.480000            X(  2) =      4500.000000
                                                X(  3) =      3500.000000
                                                X(  4) =      5000.000000
                                                X(  5) =       284.000000
                                                X(  6) =       106.000000
                                                X(  7) =       102.000000
                                                X(  8) =       102.000000
                                                X(  9) =      9000.000000
                                                X( 10) =      4500.000000
                                                X( 11) =      3500.000000
                                                X( 12) =      5000.000000
                                                X( 13) =       425.000000
                                                X( 14) =       212.000000
                                                X( 15) =       153.000000
                                                X( 16) =       153.000000
                                                X( 17) =      8000.000000
                                                X( 18) =      4980.000000
                                                X( 19) =      3382.000000
                                                X( 20) =      4702.400000
-- More --



                                                X( 20) =      4702.400000
-- More --

                                                X( 25) =      8000.000000
                                                X( 26) =      4090.000000
                                                X( 27) =      3205.000000
                                                X( 28) =      4600.000000
```

```
WRANGE( 1,1) =        .400000       WRANGE( 1,2) =        .400000      :
WRANGE( 2,1) =        .600000       WRANGE( 2,2) =        .600000      :

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .4000    .6000

                         1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                   BASIC VARIABLE VALUES

    1        Z( 1) =     68742.920000           X(   1) =       9000.000000
             Z( 2) =     17753.480000           X(   2) =       4500.000000
                                                X(   3) =       3500.000000
                                                X(   4) =       5000.000000
                                                X(   5) =        284.000000
                                                X(   6) =        106.000000




                                                X(   7) =        102.000000
                                                X(   8) =        102.000000
                                                X(   9) =       9000.000000
                                                X(  10) =       4500.000000
                                                X(  11) =       3500.000000
                                                X(  12) =       5000.000000
                                                X(  13) =        425.000000
                                                X(  14) =        212.000000
                                                X(  15) =        153.000000
                                                X(  16) =        153.000000
                                                X(  17) =       8000.000000
                                                X(  18) =       4980.000000
                                                X(  19) =       3382.000000
                                                X(  20) =       4702.400000
-- More --
-- More --

                                                X(  25) =       8000.000000
                                                X(  26) =       4090.000000
                                                X(  27) =       3205.000000
                                                X(  28) =       4600.000000
```

```
WRANGE( 1,1) =        .300000      WRANGE( 1,2) =        .300000
WRANGE( 2,1) =        .700000      WRANGE( 2,2) =        .700000

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)



   .3000    .7000

                    1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

  BASIS          CRITERION VALUES                 BASIC VARIABLE VALUES

    1        Z( 1) =     64226.600000         X(  1) =      9000.000000
             Z( 2) =     20656.828571         X(  2) =      4500.000000
                                              X(  3) =      4571.428571
                                              X(  4) =      3500.000000
                                              X(  5) =       284.000000
                                              X(  6) =       106.000000
                                              X(  7) =       102.000000
                                              X(  8) =       102.000000
                                              X(  9) =      9000.000000
                                              X( 10) =      4500.000000
                                              X( 11) =      4571.428571
                                              X( 12) =      3500.000000
                                              X( 13) =       425.000000
                                              X( 14) =       212.000000
                                              X( 15) =       153.000000
                                              X( 16) =       153.000000
                                              X( 17) =      8000.000000
                                              X( 18) =      4980.000000
                                              X( 19) =      4275.142857
                                              X( 20) =      3452.000000
-- More --
                                              X( 20) =      3452.000000
-- More --

                                              X( 25) =      8000.000000
                                              X( 26) =      4090.000000
                                              X( 27) =      4201.428571
                                              X( 28) =      3205.000000
```

```
WRANGE( 1,1) =        .200000      WRANGE( 1,2) =        .200000    1
WRANGE( 2,1) =        .800000      WRANGE( 2,2) =        .800000    1

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

  .2000   .8000

                    1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                    BASIC VARIABLE VALUES

    1       Z( 1) =      64226.000000            X(  1) =      9000.000000
            Z( 2) =      20656.828571            X(  2) =      4500.000000
                                                 X(  3) =      4571.428571
                                                 X(  4) =      3500.000000
                                                 X(  5) =       284.000000
                                                 X(  6) =       106.000000
                                                 X(  7) =       102.000000
                                                 X(  8) =       102.000000
                                                 X(  9) =      9000.000000
                                                 X( 10) =      4500.000000
                                                 X( 11) =      4571.428571
                                                 X( 12) =      3500.000000
                                                 X( 13) =       425.000000
                                                 X( 14) =       212.000000
                                                 X( 15) =       153.000000
                                                 X( 16) =       153.000000
                                                 X( 17) =      8000.000000
                                                 X( 18) =      4980.000000
                                                 X( 19) =      4275.142857
-- More --                                       X( 20) =      3452.000000
-- More --

                                                 X( 25) =      8000.000000
                                                 X( 26) =      4090.000000
                                                 X( 27) =      4201.428571
                                                 X( 28) =      3205.000000
```

```
WRANGE( 1,1) =        .100000        WRANGE( 1,2) =        .100000     1
WRANGE( 2,1) =        .900000        WRANGE( 2,2) =        .900000     2

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

   .1000   .9000

                       1 REDUCED CRITERION CONE GENERATORS
-- More --
-- More --

 BASIS          CRITERION VALUES                  BASIC VARIABLE VALUES

   1        Z( 1) =     64226.600000            X(  1) =     9000.000000
            Z( 2) =     20656.828571            X(  2) =     4500.000000
                                                X(  3) =     4571.428571
                                                X(  4) =     3500.000000
                                                X(  5) =      284.000000
                                                X(  6) =      106.000000
                                                X(  7) =      102.000000
                                                X(  8) =      102.000000
                                                X(  9) =     9000.000000
                                                X( 10) =     4500.000000
                                                X( 11) =     4571.428571
                                                X( 12) =     3500.000000
                                                X( 13) =      425.000000
                                                X( 14) =      212.000000
                                                X( 15) =      153.000000
                                                X( 16) =      153.000000
                                                X( 17) =     8000.000000
                                                X( 18) =     4980.000000
                                                X( 19) =     4275.142857
                                                X( 20) =     3452.000000
-- More --

-- More --                                      X( 20) =     3452.000000


                                                X( 25) =     8000.000000
                                                X( 26) =     4090.000000
                                                X( 27) =     4201.428571
                                                X( 28) =     3205.000000
```

Appendix G: Interval Search For Weighting Assignments Solution Results in ADBASE Output Format

NOTE: The entire output is over 200K bytes in length; therefore, then first and last efficient bases are given. The intent of this appendix is to illustrate how much work would be required to plot each efficient basis' convex cone components.

WRANGE(1,1) = .300000 WRANGE(1,2) = 1.000000 .
WRANGE(2,1) = .300000 WRANGE(2,2) = 1.000000 1

PREMULTIPLICATION T-MATRIX (SEE PP. 246-251)

.7000	.3000
.3000	.7000

2 REDUCED CRITERION CONE GENERATORS

BASIS CRITERION VALUES ALL BASIC VARIABLE VALUES

C(J)-Z(J) REDUCED COSTS

21	22	23	24	30
33	35	41	42	43
44	45	46	47	48
49	50	51	52	53
55	57	58	59	61
62	63	64	77	78
79	80	81	82	83
84	85	86	87	88
89	90	91	92	93
94	95	96	97	98
99	100	101	102	103
104	105	106	107	108

-960.00000	-878.00000	-924.00000	-548.00000	-1.12000
-1.12000	-.60000	-1015.60000	-748.00000	-795.24000
-470.88000	-805.00000	-667.00000	-761.80000	-453.60000

-- More --
-- More --

-7.00000	-.60000	-7.00000	-.60000	-6.40000
-1.12000	-9.00000	-1.00000	-1.40000	-160.00000
-160.00000	-160.00000	-200.00000	.00000	1.12000
.00000	.00000	1.12000	.00000	.60000
.00000	.00000	.00000	.00000	.00000
1015.60000	748.00000	795.24000	470.88000	805.00000
667.00000	761.80000	453.60000	7.00000	.60000
7.00000	.60000	6.40000	.00000	1.12000
.00000	9.00000	1.00000	1.40000	.00000
-192.00000	-175.60000	-184.80000	-109.60000	.72000
.72000	-.40000	-253.60000	-186.80000	-197.72000
-117.64000	-201.20000	-166.80000	-189.36000	-113.32000
-2.00000	-.40000	-2.00000	-.40000	-1.60000
.72000	-2.00000	-.40000	.72000	-40.00000
-40.00000	-40.00000	-40.00000	.00000	-.72000
.00000	.00000	-.72000	.00000	.40000
.00000	.00000	.00000	.00000	.00000
253.60000	186.80000	197.72000	117.64000	201.20000
166.80000	189.36000	113.32000	2.00000	.40000
2.00000	.40000	1.60000	.00000	-.72000
.00000	2.00000	.40000	-.72000	.00000

..

```
-------------------------------------------------------------

36      Z( 1) =     69662.920000          X(  1) =     9000.000000
        Z( 2) =     17753.480000          X(  2) =     4500.000000
                                          X(  3) =     3500.000000
                                          X(  4) =     5000.000000

  C(J)-Z(J) REDUCED COSTS
      21            22            23            24            30
        33            35            39            41            42
        43            44            45            46            47
        48            49            50            51            52
        53            55            57            58            61
        62            63            64            77            78
        79            80            81            82            83
        84            85            86            87            88
        89            90            91            92            93
        94            95            96            97            98
        99           100           101           102           103
       104           105           106           107           108
-------------------------------------------------------------
  -960.00000    -878.00000    -924.00000    -548.00000      -1.12000
      -1.12000       -.60000      -1.40000   -1015.60000    -748.00000
    -793.84000    -470.88000    -805.00000    -667.00000    -760.40000
    -453.60000      -7.00000       -.60000      -7.00000       -.60000
      -6.40000      -1.12000      -9.00000      -1.00000    -160.00000
    -160.00000    -160.00000    -200.00000        .00000       1.12000
        .00000        .00000       1.12000        .00000        .60000
        .00000        .00000        .00000       1.40000        .00000
    1015.60000     748.00000     793.84000     470.88000     805.00000
     667.00000     760.40000     453.60000       7.00000        .60000
       7.00000        .60000       6.40000        .00000       1.12000
        .00000       9.00000       1.00000        .00000        .00000
-- More --
-- More --

  -192.00000    -175.60000    -184.80000    -109.60000        .72000
        .72000       -.40000        .72000    -253.60000    -186.80000
    -198.44000    -117.64000    -201.20000    -166.80000    -190.08000
    -113.32000      -2.00000       -.40000      -2.00000       -.40000
      -1.60000        .72000      -2.00000       -.40000     -40.00000
     -40.00000     -40.00000     -40.00000        .00000       -.72000
        .00000        .00000       -.72000        .00000        .40000
        .00000        .00000        .00000       -.72000        .00000
     253.60000     186.80000     198.44000     117.64000     201.20000
     166.80000     190.08000     113.32000       2.00000        .40000
       2.00000        .40000       1.60000        .00000       -.72000
        .00000       2.00000        .40000        .00000        .00000
-------------------------------------------------------------

NUMBER OF COMPUTED EFFICIENT BASES         =   36
NUMBER OF EFFICIENT EXTREME POINTS         =    9
NUMBER OF UNBOUNDED EFFICIENT EDGES        =    0

*********1*********2*********3*********4*********5*********6*********7**
```

Appendix H: Vehicle Acquisition Model in Tableau Format

(Go on to next page).

[illegible]LE ACQUISITION TABLEAU

	X_{51}	X_{61}	X_{71}	X_{81}	X_{12}	X_{22}	X_{32}	X_{42}	X_{52}	X_{62}	X_{72}	X_{82}	X_{13}	X_{23}	X_{33}	X_{43}	X_{53}	X_{63}	X_{73}	X_{83}	X_{14}	X_{24}	X_{34}	X_{44}	X_{54}	X_{64}	X_{74}	X_{84}			
1)	.05	.01	.007	.005																									≤	544.50	B
2)					6.29	4.64	4.95	2.93	.05	.01	.007	.005																	≤	3626.46	U
3)					.03	.02	.009	.008					5.0	4.15	4.75	2.83	.05	.01	.007	.005									≤	4673.90	D
4)					.03	.02	.009	.008					.03	.02	.009	.008					4.8	4.39	4.62	2.74	.05	.01	.007	.005	≤	518.30	G
5)					1.0																								≤	335.0	
6)						1.0																							≤	125.0	
7)							1.0																						≤	120.0	M
8)								1.0																					≤	120.0	A
9)													1.0																≤	500.0	X
10)														1.0															≤	250.0	
11)															1.0														≤	180.0	P
12)																1.0													≤	180.0	R
13)																					1.0								≤	500.0	O
14)																						1.0							≤	250.0	D
15)																							1.0						≤	180.0	
16)																								1.0					≤	180.0	–
17)	1.0	1.0																											≥	13500.0	
18)			1.0																										≥	3500.0	
19)				1.0																									≥	3500.0	L
20)									1.0	1.0																			≥	13500.0	B
21)											1.0																		≥	3500.0	
22)												1.0																	≥	3500.0	F
23)					1.0	1.0											1.0	1.0											≥	13370.0	S
24)							1.0												1.0										≥	3484.0	
25)								1.0												1.0									≥	3554.0	
26)													1.0	1.0											1.0	1.0			≥	13117.0	
27)															1.0												1.0		≥	3460.0	
28)																1.0												1.0	≥	3460.0	–
29)					1.0																								≥	284.0	
30)						1.0																							≥	106.0	M
31)							1.0																						≥	102.0	I
32)								1.0																					≥	102.0	N
33)													1.0																≥	425.0	T
34)														1.0															≥	212.5	C
35)															1.0														≥	153.0	H
36)																1.0													≥	153.0	–
37)	1.0																												≥	9000.0	
38)		1.0																											≥	4500.0	L
39)									1.0																				≥	9000.0	B
40)										1.0																			≥	4500.0	
41)																	1.0												≥	8000.0	H
42)																		1.0											≥	4980.0	F
43)																			1.0										≥	3382.0	V
44)																				1.0									≥	3452.0	
45)																									1.0				≥	8000.0	
46)																										1.0			≥	4090.0	
47)																											1.0		≥	3205.0	
48)																												1.0	≥	3205.0	–

Appendix I: Shadow Price (Duality) Output

(Go on to next page).

```
TABLEAU WITH C(J)-Z(J) REDUCED COSTS
      21               22               23               24               29
         30               32               33               35               41
         42               43               44               45               46
         47               48               49               51               53
         55               57               58               59               61
         62               63               64               77               78
         79               80               81               82               83
         84               85               86               87               88
         89               90               91               92               93
         94               95               96               97               98
         99              100              101              102              103
        104              105              106              107              108
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
-960.00000       -878.00000       -924.00000       -548.00000        -.60000
     -1.12000         -.60000         -1.12000         -.60000    -1015.60000
   -748.00000     -795.24000       -470.88000       -805.00000     -667.00000
   -761.80000     -453.60000         -6.40000         -6.40000       -6.40000
     -1.12000       -9.00000         -1.00000         -1.40000     -160.00000
   -160.00000     -160.00000       -200.00000           .60000        1.12000
       .00000         .60000          1.12000           .00000         .60000
       .00000         .00000           .00000           .00000         .00000
   1015.60000      748.00000        795.24000        470.88000      805.00000
    667.00000      761.80000        453.60000          6.40000         .00000
      6.40000         .00000          6.40000           .00000        1.12000
       .00000        9.00000          1.00000          1.40000         .00000
-192.00000       -175.60000       -184.80000       -109.60000        -.40000
       .72000        -.40000           .72000          -.40000     -253.60000
   -186.80000     -197.72000       -117.64000       -201.20000     -166.80000
   -189.36000     -113.32000         -1.60000         -1.60000       -1.60000
       .72000       -2.00000          -.40000           .72000      -40.00000
    -40.00000      -40.00000        -40.00000           .40000        -.72000
       .00000         .40000          -.72000           .00000         .40000
       .00000         .00000           .00000           .00000         .00000
    253.60000      186.80000        197.72000        117.64000      201.20000
-- More --
-- More --

    166.80000      189.36000        113.32000          1.60000         .00000
      1.60000         .00000          1.60000           .00000        -.72000
       .00000        2.00000           .40000          -.72000         .00000



--------------------------------------------------------------------------------
```

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Vita

Captain Joseph P. DiSalvo graduated from the United States Military Academy in May 1981, receiving a Bachelor of Science degree in Management. Upon completion of the Junior Officer Maintenance Course and Armor Officer Basic Course, he was assigned to the 3rd Armored Cavalry Regiment from 1982 to 1985 at Fort Bliss, Texas where he served as tank platoon leader, tank company executive officer, and squadron motor officer. After completing the Armor Officer Advanced Course he was assigned to 1-13th Armor Battalion in Vilseck, FRG. From 1985 to 1988 he served as battalion motor officer, commander Company A and Headquarters & Headquarters Company commander. Additionally, CPT DiSalvo is airborne/ranger qualified. CPT DiSalvo entered the School of Engineering, Air Force Institute of Technology, in August 1988, and graduated in March 1990 with a Master of Science degree in Operations Research.

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11. TITLE (Include Security Classification) A GOAL-SEEKING APPROACH TO MODEL THE INJECTION OF FUTURE VEHICLES INTO THE U.S. ARMY INVENTORY

12. PERSONAL AUTHOR(S) Joseph P. DiSalvo CPT USA

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this study was to develop a quantitative decision aid to augment the subjective assessment prioritization of future vehicle acquisition. The objective of this study was to develop a quantitative methodology that models the acquisition of future vehicles into the U.S. Army inventory.

Instead of establishing inventory levels based on individual vehicle priorities, this study approached establishing inventory levels based on mission priorities. By using a Goal-Seeking Multiparametric Decomposition model, an illustrative example was processed resulting in specific inventory levels for all vehicles peculiar to an associated mission. Sensitivity was conducted to demonstrate how the inventory levels were effected as the priorities of each mission changed.

(continued on reverse)

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